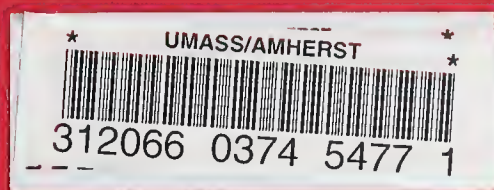


MASS. EA12.2: C37/v.2



Volume II

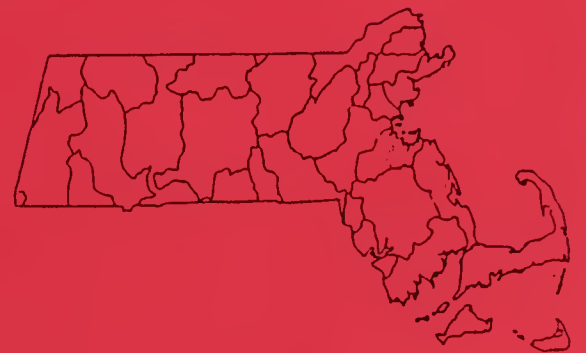
Charles River Basin

Hydrologic Analysis & Recommendations For A Minimum Streamflow Threshold

GOVERNMENT DOCUMENTS
COLLECTION

FEB 7 1991

University of Massachusetts
Depository Copy



October 1989

Massachusetts Executive Office of Environmental Affairs
Department of Environmental Management
Division of Water Resources

Michael S. Dukakis, Governor ○ John P. DeVillars, Secretary EOEA ○ Richard E. Kendall, Commissioner DEM

904/23

CHARLES RIVER BASIN

VOLUME II

Hydrologic Analysis and
Recommendations for a Minimum Streamflow Threshold

prepared for the

Massachusetts Water Resources Commission
Executive Office of Environmental Affairs

Department of Environmental Management
Division of Water Resources

Richard H. Thibedeau
Director

October 1989

Publication No. 16,399-92-150-7-90-CR
Approved by Ric Murphy, State Purchasing Agent

EXECUTIVE SUMMARY

CHARLES RIVER BASIN, VOLUME II

I. Hydrology

The Charles River drains 311 square miles along its 80 mile length. Over the past 55 years, the monthly average flows range from approximately 140 cubic feet per second (cfs) to 910 cfs at the mouth of the river. The low flow months on the Charles River predominantly are June through October, while the high flows generally occur between February and April.

The upper part of the basin contains extensive wetland areas which buffer peak flows and slow the response of the river to precipitation events. During dry periods the aquifers underlying the river contribute a large portion of the flow during dry periods. During extremes of precipitation and drought, however, these buffering characteristics are less effective.

There are three gages that measure and record the river flow. The Dover gage measures a drainage area of 183 square miles; the Wellesley gage measure flows from 211 square miles; and the Waltham gage measures flow from 250 square miles.

Mother Brook, located in Dedham, is an artificial diversion of water from the Charles River to augment the flow in the Neponset River and to reduce flood flows in the Charles. Due to this diversion, during high flow periods, the flow per square mile of watershed is higher at Dover than at the other gages.

The hydrologic conditions of the 1980-1981 drought, which has a recurrence interval of approximately one in 24 years, were selected to test the reliability of water supply systems that depend on the water resources of the Charles River basin. Most stress to water supply systems occurs during the summer and early fall when evapotranspiration and water supply demand are at their peak and water levels generally are at their annual low point.

II. Subbasin Yield Analysis

Subbasin yield is an expression of how much water is available for use within a subbasin. The analysis examined subbasin yields which were available 95 and 99 percent of the time during the 1980's drought and for the adjusted period of record. For this study, the flow available 99 percent of the time is considered the subbasin yield. Subbasin yields using the adjusted period of record have

been calculated for comparison. For the 99 percent flow duration during the 1980-1981 period, available subbasin yields ranged from 0.1 cfs to 3.1 cfs.

In order to quantify the volume of water available in the subbasins of the Charles River, two methods were used: the Index Station Method and the Aquifer Yield method. Both methods provide yields based on flow duration curves for the subbasins being analyzed. The analysis considers only the 16 subbasins of the upper basin (above the Waltham gage). Except for Cambridge and Lincoln, communities downstream of the Waltham gage are fully supplied by the Massachusetts Water Resources Authority which obtains water from the Chicopee and Nashua River basins.

The Index Station method was used in the subbasins upstream of the Dover gage because existing hydrogeological conditions make it more appropriate than the Aquifer Yield method. The index station method establishes a relationship between two streamflow gaging stations for a short-term period of concurrent record by plotting the discharges for given base flow measurements at a station in the subbasin against discharges at the index station. The index station is the selected streamflow gaging station of continuous long term record. Base flows are low flows, predominantly from ground water infiltration, which occur after periods of low precipitation and runoff. Once a relationship has been established between the index station and the subbasin, the base flows for various flow durations can be calculated for the subbasin. The 99 percent flow was obtained for the index station and for each subbasin. These values, calculated for the planning drought conditions, are the subbasin yields.

To insure a valid correlation between the subbasin and the index station, it was assumed that streamflow conditions in the two subbasins should be as close to base flow conditions as possible. Data from two precipitation stations was used to verify the existence of base flow conditions on the day of the streamflow record. An analysis was also carried out to determine the response time of a significant precipitation event on the index station.

The Aquifer Yield method was used for subbasins between the Waltham gage and the Dover index station. These subbasins are heavily influenced by human activities and lend themselves more readily to the Aquifer Yield method. This method uses yields calculated by the U.S. Geological Survey based on the amount of water available through ground water recharge/discharge.

In order to insure the best correlation, the yields calculated by both methods have been adjusted to reflect virgin streamflow conditions without the influence of

existing or historic demand. The inflows and outflows were determined seasonally in each subbasin and at the index station for the years during which the flows occurred and were measured. The streamflow effects of new reservoirs, wells, and sewage treatment plants also were taken into consideration.

In the five subbasins below the Dover gage, the 1980's drought yields range from 0.7 cfs in the Charles River-Route 128 subbasin at the 99 percent flow duration to 5.2 cfs at the Charles River/Wellesley subbasin.

Several subbasins appear to have adequate yield available, while other subbasins appear significantly overstressed. For example, the Fuller/Waban Brook, Charles River/Dover and the Stony Brook subbasins use more water on a daily basis than is available during the simulated 1980's drought. Current demand, under planning drought conditions, would be met either through induced infiltration from the Charles River or through surface water storage. Yield available at Rosemary Brook is approximately equal to the net demand in the subbasin.

III. Accounting Model Methodology and Results

The hydrologic model of the Charles River includes a simulation of the three main physical components of the basin hydrology: the main stem; a localized aquifer, because most of the ground water is in isolated aquifers with close hydraulic connection to the stream; and off-channel storage, in the case of Cambridge. Each subbasin is identified and the water use for each is calculated. In each subbasin, the model accounts for towns, reservoirs, wells, and wastewater treatment plants, and other physical objects that affect water use.

The model simulates the continuous interactions of the real world by cycling through discrete passes at monthly intervals. Each pass carries out specific functions of addition or subtraction to streamflow due to runoff, well pumpage, recharge of aquifers, streamflow diversions, and other activities. The model includes the withdrawals from surface storage and municipal demands.

Extensive data collection was needed to accurately reflect the physical and operational parameters for the simulation program. Data included subbasin drainage areas, location of reservoirs and their drainage areas; pumping capacities and location of wells; the effects on streamflow of well pumpage based on transmissivity and specific yield on the aquifer and distance to the stream; seasonal demand for water by communities; sewage return through sewage or septic effluent weighted according to the percentage of water users that are sewered or not; and the engineering operating rules of the .

water supply system in each community and each community source.

The model simulated the affect of the operation of fifteen water supply systems on streamflow through the year 2020 under conditions of the 1980's drought. In addition, the model simulated the ability of each system's supplies to meet the community's demand. Only five communities are not projected to have any type of deficit with projected water demands. Four communities are expected to have average day demand deficits throughout the period, meaning that they will fail to meet demand with existing sources. Seven communities are expected to experience average or maximum day demand deficits at some time between 1995 and 2020. The drought conditions under which these deficits are projected to occur can be expected approximately once in 24 years.

A minimum streamflow is included in the model as a threshold below which significant detrimental effects may be incurred by fisheries, recreation, wildlife, and other instream uses. Different water supply and conservation scenarios were run in the model to determine the scenario which would produce the highest reasonable streamflow level.

IV. Minimum Streamflow Threshold

The goal of determining a minimum streamflow threshold is to achieve a balance between water uses which depend on the river. The estimated streamflow requirements and locations of existing and planned consumptive and non-consumptive uses in the Charles River were identified. The available flow at each location was calculated and compared to the estimated flow needs for each water use. The minimum streamflow threshold was tested iteratively to determine a reasonable level while protecting the environmental quality of the basin. The flow of 0.21 cfs per square mile of watershed was found to best balance the instream and out-of-stream needs identified in the planning process.

TABLE OF CONTENTS

	<u>PAGE</u>
Executive Summary	i
List of Tables	vi
List of Figures	vii
Preface	ix
I. HYDROLOGIC ANALYSIS	1
A. Hydrology of the Charles River Basin	1
B. Planning Drought Analysis	6
1. Planning Drought Selection	8
2. Drought Recurrence	9
II. SUBBASIN YIELD ANALYSIS	12
A. Index Station Method (Upstream of Dover gage)	12
1. Data Collection	14
2. Demand Adjustment	14
3. Data Quality Control	15
4. Baseflow Station/Index Station Correlation	17
5. Yield Derivation	31
B. Aquifer Yield Method (Downstream of Dover gage.)	32
1. USGS Aquifer Yield Prediction Methodology	32
2. Subbasin Yields (Below Dover Gage)	35
C. Subbasin Inflows and Outflows	37
D. Existing Subbasin Yields	40
III. HYDROLOGIC ACCOUNTING MODEL OF THE CHARLES RIVER	43
A. Methodology	43
B. Results	47
IV. MINIMUM STREAMFLOW THRESHOLD	50
A. Introduction	50
B. Methodology	50
C. Charles River Streamflow	51
D. Inventory of Water Uses	52
1. Resident Fisheries	53
2. Marine Fisheries	57
3. Receipt of Treated Wastewater Effluent	59
4. Municipal Water Supply	62
5. Scenic Rivers	64
6. Recreation	66
7. Forests and Parks	68
8. Wetlands	70
9. Agriculture	72
10. Rare Plant Species	74
E. Summary	76
V. REFERENCES	77

LIST OF TABLES

	<u>PAGE</u>
1. River Basin Planning Format	x
2. Charles River gage at Dover, Recurrence Intervals	10
3. Charles River Basin Subbasins	13
4. Estimated Virgin Yields of Subbasins Upstream of the Charles River at Dover gage	33
5. Estimated Virgin Yields of Charles River Main Stem Subbasins Upstream of the Dover Gage	34
6. Estimated Virgin Subbasin Yields Downstream of the Charles River Dover Subbasin	36
7. Estimated Subbasin Yields, Charles River Basin, Early 1980's Drought	41
8. Charles River Basin - Base and Projected Average Day Water Demand	46
9. Summary of Model Results	48
10. Wastewater Treatment Plants and other Discharges	61

LIST OF FIGURES

	PAGE
1. Charles River Basin Subbasins and Gaging Stations	2
2. Flow Duration Curves for the Charles River, Dover Gage, Wellesley Gage, and Waltham Gage, 1960-1987	4
3. Flow Duration Curves for the Charles River, Dover Gage; 1960-1987 and 1980-1981	5
4. Monthly Flows - Charles River, Dover Gage, Period of Record	7
5. Plot of Recurrence Interval Versus Discharge, Charles River at Dover Gage	11
6. Sample Water Resources Commission Precipitation Record	16
7. Examples of Streamflow Response to Precipitation Events at the Charles River at Dover Gage	18
8. Upper Charles River/Charles River at Dover (Index Station) Flow Correlation	20
9. Hopping Brook/Index Station Flow Correlation	21
10. Mine Brook/Index Station Flow Correlation	22
11. Chicken Brook/Index Station Flow Correlation	23
12. Mill River/Index Station Flow Correlation	24
13. Charles River Millis/Index Station Flow Correlation	25
14. Stop River/Index Station Flow Correlation	26
15. Bogastow Brook/Index Station Flow Correlation	27
16. Charles River Medfield/Index Station Flow Correlation	28
17. Fuller and Waban Brook/Index Station Flow Correlation	29
18. Charles River at Dover/Index Station Flow Correlation	30
19. Model Results: Community Water Supply Status	49

20. Division of Fisheries and Wildlife, Mixed Warm Water Species	54
21. Division of Fisheries and Wildlife, Marginal and Seasonal Cold Water, and Lowland Warm Water Fisheries	55
22. Division of Fisheries and Wildlife, Upland and Lowland Cold Water Fisheries	56
23. Division of Marine Fisheries, Existing Migration Routes, Planned Migration Routes and Dam Locations.	58
24. Division of Water Pollution Control, Wastewater Treatment Plants, and Wastewater Classifications	60
25. Charles River Basin Water Supply Sources	63
26. Scenic Rivers Program, Office of Planning and Development; DEM, Scenic Rivers Designations	65
27. Charles River Watershed Association Appalachian Mountain Club River Guide: Canoeing, Kayaking, Sailing, Rowing and Power Boating	67
28. Division of Forests and Parks, DEM: State Forests and Reservations with Water Based Recreation	69
29. U.S. Army Corps of Engineers; Soil Conservation Service; University of Massachusetts, Amherst; Metropolitan Area Planning Council; Massachusetts Water Resources Commission: Wetlands and Natural Valley Storage Areas	71
30. Department of Agriculture; Division of Water Supply, DEP : Golf Courses	73
31. Massachusetts Natural Heritage Program, Division of Fisheries and Wildlife, DFWELE : Rare and Endangered Plant Species	75

PREFACE

The Massachusetts Water Resources Commission has the primary responsibility for determining state water resources policy and directing water resources planning activities for the Commonwealth through the Executive Office of Environmental Affairs. The Division of Water Resources (DWR), in the Department of Environmental Management, provides technical staff support to the Commission and is responsible through the Commission for long-range water resources engineering and planning for the Commonwealth. The central element in the development of the statewide water resources management plan is the preparation of a management plan for each of the twenty-seven river basins of the Commonwealth. These plans are being developed pursuant to the Water Resources Planning Regulations, 313 CMR 2.00. The basin planning process includes local, regional, and state assessments of water needs and the availability of water resources. The plans are in conformance with the Massachusetts Water Supply Policy Statement and are consistent with other water-related state and federal laws and regulations. The river basin planning process (Table 1) consists of five steps:

1. Development of an inventory of the basin's water uses
2. Analysis of data and identification of the future water needs in the basin
3. Development and analysis of alternatives to meet projected water needs
4. Preparation of the basin-specific water resources management plan for approval by the Water Resources Commission
5. Adoption of the plan

The river basin planning program is part of the state's overall goal of ensuring that water is available in sufficient quantity and quality to meet current and future consumptive and non-consumptive water needs for Massachusetts.

Volume I of the Charles River Basin Plan consists of the inventory step of the planning process. It includes the collection of existing data on the river basin's current and projected water demand, active water supply sources, and short- and long-term demographic profiles for communities in the study area.

Volume II includes a Subbasin Yield (SUBY) Analysis, an assessment of communities' ability to meet projected water demands, and a recommendation for a minimum streamflow threshold. A hydrologic simulation model developed by the U.S. Geological Survey was utilized to determine which communities may not be able to meet future demands (deficit communities)

Table 1

MASSACHUSETTS DEPARTMENT OF ENVIRONMENTAL MANAGEMENT

DIVISION OF WATER RESOURCES
RIVER BASIN PLANNING PROGRAM

RIVER BASIN PLANNING FORMAT

STEP 1	STEP 2	STEP 3	STEP 4	STEP 5
DEVELOP INVENTORY OF BASIN SUPPLY AND DEMAND	ANALYZE BASIN INVENTORY AND IDENTIFY FUTURE WATER NEEDS	DEVELOP AND ANALYZE ALTERNATIVES TO MEET PROJECTED NEEDS	PREPARE WATER RESOURCES MANAGEMENT PLAN	ADOPT PLAN
(a) Demographic profile of each Community from Federal, State, Regional and Community Studies.	(a) 1995-2020 population changes of each community.	(a) Local alternatives to meet projected community water needs (conservation, infrastructure storage, interconnections with contiguous communities).	(a) Selection by WRPTP for Step 3(d) communities of the best mix of new local and regional alternatives (Step 3 a & b) to meet deficits.	(a) WRC review of final draft plan.
(b) Historical and existing water demand of each community.	(b) 1995-2020 projected water demand of each community.	(b) Preliminary regional alternatives (MWRA, diversions, new regional reservoirs, interconnection).	(b) Selection of alternative(s) for all communities and basins.	(b) WRC vote on plan's adoption or adoption with modification.
(c) Existing and proposed water supply sources and systems via questionnaire replies.	(c) Existing and proposed water supply sources and systems as presented in questionnaire replies.	(c) Analysis and comparison of the relevant economic, environmental and institutional impacts of the alternatives and assessment of their ability to meet future needs.	(c) Preparation of draft plan.	
(d) Water resources management structure and organization via questionnaire replies.	(d) Conservation measures reported in questionnaire replies compared to the state conservation guidelines i.e. retrofit, leak detection, system rehabilitation, public education, ground water protection.	(d) Identification of deficient communities using local alternatives and not using regional alternatives per Step 3(b)	(d) Review and comment by local, regional, and state agencies and the Water Resources Commission on draft basin plan.	
(e) Water requirements for recreation, fish, wildlife, agriculture, hydropower and dilution.	(e) Task Force analysis of minimum streamflow thresholds.		(e) Preparation of final plan based on review comment.	
(f) Outline by DEQB of basin water quality.	(f) Relationship between available water resources, projected demand and minimum streamflow thresholds.			
(g) Unregulated historical streamflow data.	(g) Community and basin deficits.			

<----- CONTINUOUS INTERACTION WITH LOCAL, REGIONAL AND STATE AGENCIES ----->

The adopted plan is one of the factors included in decision making under the Interbasin Transfer Act, Water Resources Management Act and MWRA Contracts, as outlined in 313 CMR 2.00, Water Resources Management Planning Regulations.

during the 1995-2020 period. The SUBY analysis quantifies the supply of water in each subbasin as a basis for balancing future and existing demands under an improved minimum streamflow threshold. The streamflow threshold is determined through an iterative analysis of instream and out-of-stream flow needs, their locations, and hydrologic data.

The third volume will include recommended water resource management alternatives for basin communities, the recommended minimum streamflow threshold, and recommended conservation measures for each community.

I. HYDROLOGIC ANALYSIS

A. Hydrology of the Charles River Basin

The Charles River meanders across 80 miles and drains 311 square miles as it flows to the Atlantic Ocean. The Charles River's headwaters are in Hopkinton near Echo Lake. From the outlet of Echo Lake, at 347 feet above mean sea level, the river flows through hilly areas in Milford, Bellingham and Franklin, through the wetland areas in the middle of the basin to its mouth in Boston Harbor. The river basin boundary (Figure 1) includes portions of thirty communities upstream of the Waltham streamflow gage, and nine between Waltham and Boston Harbor.

Glacial deposits of sand and gravel (stratified drift) cover 47 percent of the basin (USGS, GIS 1989), predominantly in the lowland areas. These sand and gravel aquifers underlying the river, discharge water to the river and are especially important in maintaining flow during periods of low precipitation. Till and outcrop cover 53 percent of the basin, primarily in the upland portions. The extensive wetland areas along the river in the upper part of the basin and the aquifers underlying the river have a combined effect of decreasing the range over which the flow varies. The wetlands buffer peak flows and the aquifers buffer the low flows. However, extreme precipitation events or droughts may render these buffering factors ineffective.

The average annual flow in the Charles River at the mouth is approximately 400 cubic feet per second (cfs). The monthly average flow can vary from approximately 140 cfs in September to 910 cfs in March. In general, the flow in the river does not fluctuate rapidly over this range, but rises slowly in response to precipitation events and drops slowly in response to periods without precipitation. Average annual precipitation is 45.97 inches per year at the Franklin precipitation station and 43.81 inches per year at the Charles River pumping station at Needham.

The flow in the river is measured at 3 points. The Dover gage, located at river mile 34 (miles above the mouth), has measured flow since 1938 for a drainage area of 183 square miles. The Wellesley gage, located at river mile 20, below a drainage area of 211 square miles has been in place since 1960. The Waltham gage, located at river mile 12, has measured flow for 250 square miles since 1932. Mother Brook, which diverts water from the Charles River to the Neponset River is located between the Dover gage and the Wellesley gage. The gage on Mother Brook has measured flow since 1932. A gage was installed in Millis in 1975 but was discontinued in 1980.

The quality of the data from the river gages is good; however, measurements prior to 1960 at the Dover gage were affected by extensive flow regulation. Flows as low as 0.90 cfs were recorded in 1941, 1952, and 1957. These flows are not representative of the flows measured during the rest of the

Figure 1



DEM: Division of Water Resources

period and have been omitted from the data analyzed in this report. In accordance with the U.S. Geological Survey Chapter 800 study of the Charles River, the period of record used in this study is 1960-1987.

The range of high and low flows can be illustrated using the historic daily flows measured at the 3 gages and the historic monthly flows obtained from the daily flows. The flow duration curve, which is calculated from the daily flows, is a useful tool for describing the low and high flows of a river as well as determining the river's characteristics along its length. The flow duration curve represents the flow which is equaled or exceeded a given percent of the time. For example, the 90 percent flow is the flow which is equaled or exceeded 90 percent of the time. Conversely, this relatively low flow can be viewed as the level below which the flow drops only ten percent of the time.

The flow duration curves in Figure 2 illustrate the flows at the Dover, Wellesley and Waltham gages. Flow increases downstream, resulting in higher measurements at the Waltham gage than at the Dover gage. However, the flows plotted in these curves are normalized to represent the flow contributed by each square mile of drainage area above the gage. Because all the flows are in the same units (cubic feet per second per square mile) they can be compared. When a river basin has uniform geographic and geohydrologic characteristics and no diversions along its entire length, the flow per square mile remains the same and the curves at different stations plot one on top of the other. In the case of the Charles River, the curves do not overlap, indicating that the flow per square mile of drainage area is not uniform. However, the average annual flow per square mile is nearly the same at each gage, and the curves overlap at that point.

During periods of high flow and low flow, the flow per square mile is highest at Dover and lower at Waltham and Wellesley. Low flows are affected by municipal water use which is seweraged out of the basin below Dover. High flows are affected by the diversion of flows through Mother Brook. Mother Brook in Dedham, artificially connected to the Charles River since 1639, diverts water from the Charles River to the Neponset River. This connection was made official by an agreement in 1831 to alleviate flood flows in the Charles River and to augment flow in the Neponset River to meet industrial needs. Currently, the Mother Brook diversion is managed by the Metropolitan District Commission.

The curves also illustrate the sluggish response of the river to changes in precipitation. The curves are rounded at the upper and lower ends indicating the flows do not fluctuate rapidly. A steep curve would indicate flashy flows. Flow duration curves can be derived for shorter periods of time as well as for the period of record. Figure 3 shows the period of record curve for the Dover gage and the 1980-1981

Figure 2

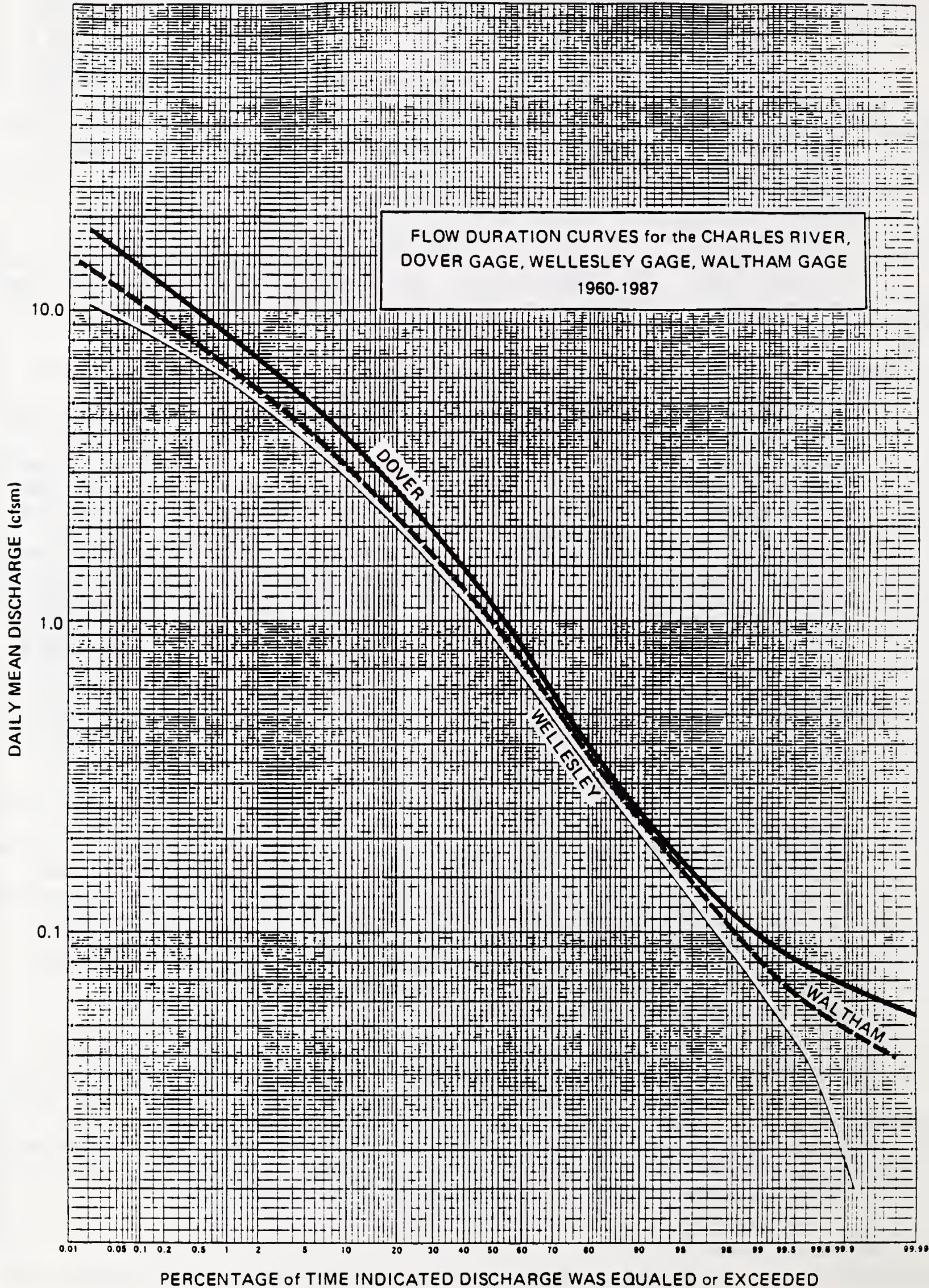
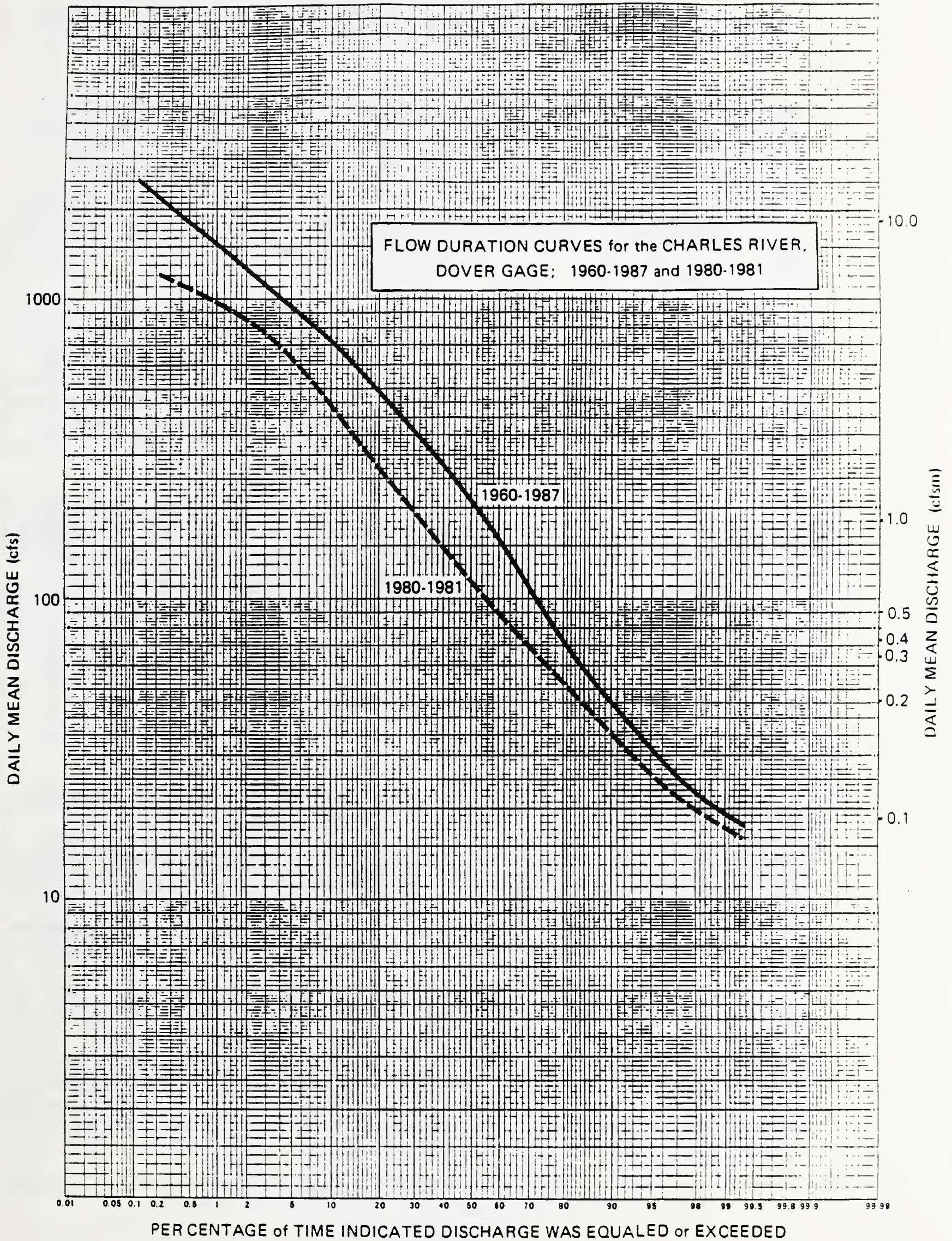


Figure 3



curve for the 1980's planning drought. Because the drought had lower than average flows, the 1980-1981 curve is below the period of record curve.

A plot of the average monthly flows at the Dover gage (Figure 4) illustrates the change in river levels throughout the year. The low flow months on the Charles River are June through October. The high flow months are February through April. Although precipitation is fairly constant throughout the year, the high rate of evapotranspiration during the summer and early fall results in lower flows. The low evapotranspiration and the snow melt in the late winter and early spring result in higher flows.

The highest flow month is March, with an average flow of 651 cfs (3.56 cfs) at the Dover gage. The lowest flow month is September (August has approximately the same flow) with an average flow of 84 cfs (0.46 cfs) at the Dover gage. However, many of the daily flows in September and August are much lower than 84 cfs. The low flows are so small that short periods of increased flows can overshadow extensive periods of low flows and result in a misleading average monthly flow.

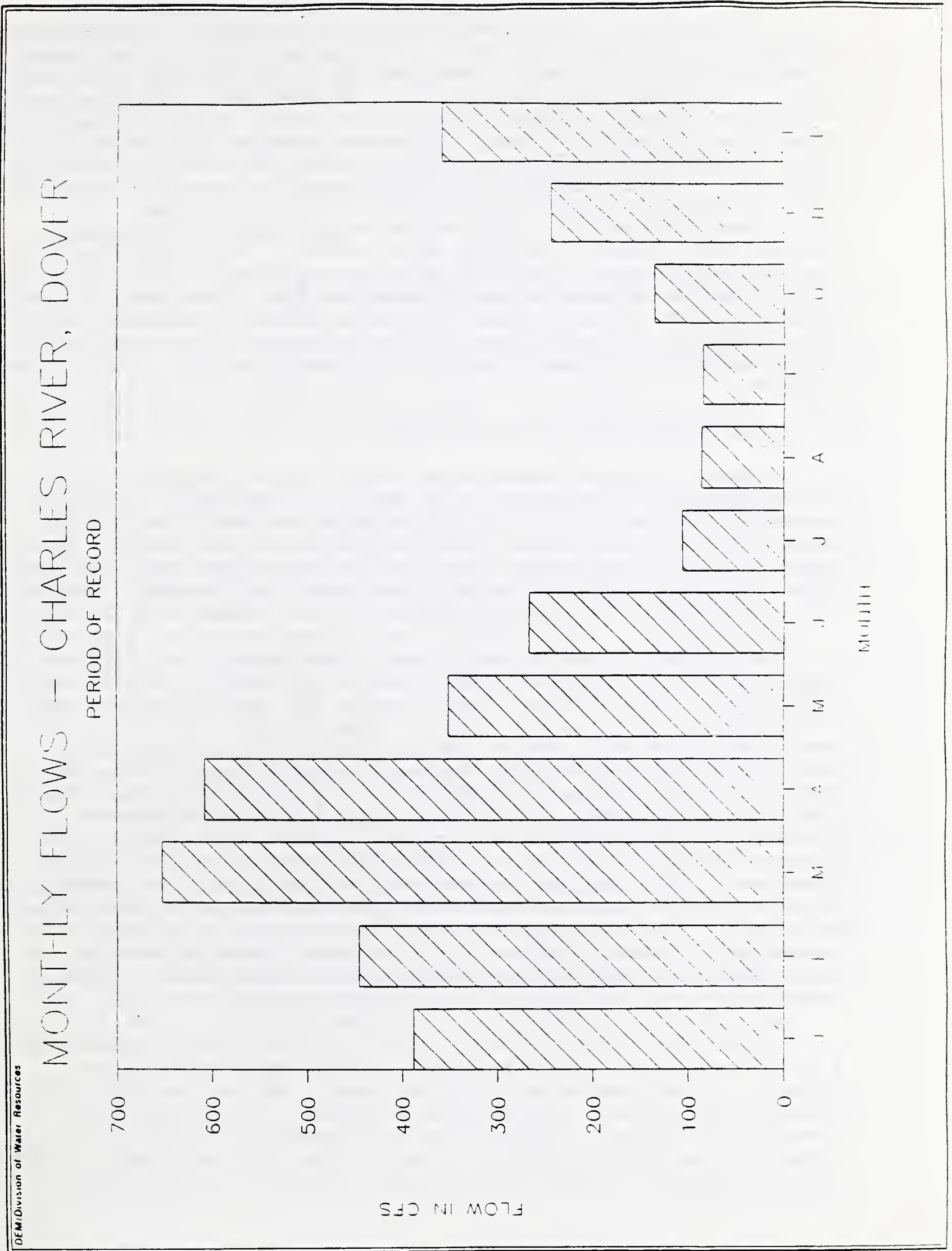
This fact is illustrated by the skew of the average monthly flows, which is a statistical parameter indicating the degree to which data may be grouped towards one extreme; in this case the high flows. For the months of February through April the average skew is 0.79, but for the months of June through October the skew is 1.47, nearly twice the skew of the high months. For example, in 1969 the average September flow was 86 cfs (0.47 cfs). Over one half the month (17 days) was below 86 cfs, with 17 days averaging 52 cfs (0.28 cfs). Therefore, daily low flows can be expected to be less than 84 cfs (0.46 cfs).

B. Planning Drought Analysis

Performance of a water supply system is directly related to hydrologic conditions. Because hydrologic conditions are dynamic and unpredictable, it is not reasonable to design a system based on average hydrologic conditions and expect them to be consistent in the future. The severity and duration of dry periods must be considered in planning for the future, and water-supply systems that respond well under average hydrologic conditions may become critically deficient during a drought.

Drought conditions are caused or perpetuated by a lack of adequate precipitation in the winter months. During the eight months of November through June, water levels should be recovering due to the relatively low rate of evapotranspiration and lower water supply demand; dry conditions during these months impede a water resource recovery. Thus, in the following summer, water levels will be reduced to even lower levels than in the previous year.

Figure 4



Hydrologically significant drought episodes in the Charles River basin historically have lasted approximately two years, except for the mid-1960's event which persisted for more than 3 years. An event less than 2 years in duration, regardless of severity, generally does not stress a water supply system or the water resources long enough to present anything more than a temporary problem. Ground water storage and surface water resources rapidly rebound to normal conditions when normal or above normal precipitation follows a single dry year. A multi-year dry period, with water supply deficits occurring particularly during the late fall, winter, and spring months, can severely hamper the ability of water supply systems to meet water demands and can present problems for other uses that depend on the river's flow. In these months, the water levels are generally at their lowest point during the year while evapotranspiration and water supply demand are at their highest levels.

1. Planning Drought Selection

Several droughts have occurred in the 49 years in which streamflow has been recorded at the U.S. Geological Survey Dover streamflow gage, #01103500. This gage accurately reflects basin-wide characteristics of the Charles River basin. Human impacts on streamflow are less at the Dover gage than at the other long-term gaging station (Waltham) in the basin because there are fewer diversions from the river above that point.

Three significant droughts were considered for simulating the effects of a dry period on the water supply systems and the hydrology of the Charles River basin: the early 1940's, the mid-1960's and the early 1980's. The drought of the mid-1960's consisted of several years of abnormally low precipitation resulting in prolonged and severe dry conditions. This dry period is the most severe over the 49 years of record. The mid 1960's drought was not used as a planning period because planning for such an extreme drought event would result in recommendations which may not be practical or economically feasible. Very few subbasins have the ability to successfully provide enough water to meet instream and out-of-stream demands in the mid 1960's drought. Under such conditions, many communities would utilize backup sources, such as standby reservoirs, as well as community interconnections, extreme restrictions on water use, and other measures.

In the Charles River basin, the 1940's drought consisted of a two year period, 1941 and 1942, which has a recurrence interval of approximately sixteen years, while the 1980-1981 drought period has a recurrence interval of approximately twenty-four years. Although not as severe in duration or intensity as the mid-1960's drought, the 1980's drought tested the abilities of local water supply systems to adequately provide water.

The 1940's and 1980's droughts are similar in hydrologic response; therefore, each would produce similar results when simulated to represent potential stressed hydrologic conditions for water supply planning purposes. However, water supply, demand, and system management data is more readily available and accurate for the early 1980's than the early 1940's period. Thus, the conditions of the early 1980's drought (1980-1981) were selected as the hydrologic conditions and planning period to be simulated in the Charles River basin.

2. Drought Recurrence

Calculating drought recurrence in the Charles River basin required several steps. The unadjusted average monthly flows of the eight months from November through June, as measured at the Dover streamflow gage (Table 2), were averaged over the period of record. The eight month averages then were averaged with the next consecutive eight month average to produce a consecutive two year, eight month average flow. This flow suggests a value which describes the hydrologic stress on a water supply system.

In response to sustained below normal rainfall beginning in late 1963, streamflow in the Charles River basin reached critical lows over the next 3 years. This trend lasted until early 1967. The November through June eight month average flows for the years 1964-65, 1965-66 and 1966-67 were 10, 50 and 60 percent, respectively, below average over the 49 year period of record. The Charles River basin experienced a dramatic hydrologic recovery beginning in early 1967. The November through June eight month average streamflow in water year 1967 returned to within 7 percent of the period of record average eight month flow.

As mentioned previously, water supply drought events in the Charles River basin have consisted primarily of two-year events, with the exception of the mid-1960's drought. For this reason the two consecutive two-year eight month periods occurring from 1964 to 1966 were averaged and ranked number one. The remaining consecutive two-year eight month averages were ranked according to severity from least to greatest starting with the second position. These drought recurrence intervals were calculated based on the 47 periods (46 two-year periods and one three-year period) and plotted (Figure 5). The results of this procedure in the Charles River basin show a yield recurrence interval of one-in-16 years for the early 1940's drought, one-in-24 years for the early 1980's drought, and one-in-48 years for the mid-1960's drought.

CHARLES RIVER GAGE AT DOVER

 SORTED AND RANKED 8 MONTH CONSECUTIVE 2-YEAR FLOW AVERAGES WITH YEARS
 1964-1966 AVERAGED AS ONE CONSECUTIVE 2-YEAR PERIOD

YEAR	8-MONTH AVERAGE ANNUAL FLOW (cfs)	8-MONTH CONSEC 2-YR FLOW AVERAGE WITH YEARS 1964-1966 AVERAGED AS ONE CONSEC 2-YR PERIOD (cfs)		SORTED LOW TO HIGH FLOWS ----- SORTED CONSECUTIVE 2-YEAR FLOWS (cfs)		RECURRENT INTERVAL ((n+1)/rank)	
		2-YEAR PERIOD	2-YR PERIOD (cfs)	2-YEAR PERIOD	2-YEAR FLOWS (cfs)	RANK	
1986	366.6						
1985	165.4	1986 - 1985	266.0	1966 - 1964	243.3	1	48.00
1984	689.7	1985 - 1984	427.6	1981 - 1980	251.3	2	24.00
1983	530.7	1984 - 1983	610.2	1942 - 1941	252.6	3	16.00
1982	534.9	1983 - 1982	532.8	1950 - 1949	263.9	4	12.00
1981	202.9	1982 - 1981	368.9	1967 - 1966	264.4	5	9.60
1980	299.8	1981 - 1980	251.3	1986 - 1985	266.0	6	8.00
1979	509.5	1980 - 1979	404.6	1944 - 1943	303.8	7	6.86
1978	572.0	1979 - 1978	540.8	1941 - 1940	308.7	8	6.00
1977	357.8	1978 - 1977	464.9	1951 - 1950	318.7	9	5.33
1976	494.8	1977 - 1976	426.3	1945 - 1944	321.5	10	4.80
1975	377.6	1976 - 1975	436.2	1943 - 1942	328.0	11	4.36
1974	460.5	1975 - 1974	419.0	1949 - 1948	354.2	12	4.00
1973	512.8	1974 - 1973	486.6	1948 - 1947	357.8	13	3.69
1972	490.8	1973 - 1972	501.8	1964 - 1963	366.5	14	3.43
1971	343.5	1972 - 1971	417.1	1982 - 1981	368.9	15	3.20
1970	526.9	1971 - 1970	435.2	1947 - 1946	380.3	16	3.00
1969	376.9	1970 - 1969	451.9	1960 - 1959	391.7	17	2.82
1968	425.8	1969 - 1968	401.3	1963 - 1962	392.5	18	2.67
1967	367.6	1968 - 1967	396.7	1968 - 1967	396.7	19	2.53
1966	161.2	1967 - 1966	264.4	1940 - 1939	397.0	20	2.40
1965	210.3	1966 - 1964	243.3	1969 - 1968	401.3	21	2.29
1964	358.4	1964 - 1963	366.5	1980 - 1979	404.6	22	2.18
1963	374.6	1963 - 1962	392.5	1958 - 1957	412.3	23	2.09
1962	410.4	1962 - 1961	432.5	1939 - 1938	413.1	24	2.00
1961	454.7	1961 - 1960	447.8	1972 - 1971	417.1	25	1.92
1960	441.0	1960 - 1959	391.7	1975 - 1974	419.0	26	1.85
1959	342.3	1959 - 1958	421.7	1955 - 1954	419.9	27	1.78
1958	501.1	1958 - 1957	412.3	1959 - 1958	421.7	28	1.71
1957	323.4	1957 - 1956	460.5	1977 - 1976	426.3	29	1.66
1956	597.6	1956 - 1955	505.8	1985 - 1984	427.6	30	1.60
1955	413.9	1955 - 1954	419.9	1962 - 1961	432.5	31	1.55
1954	425.9	1954 - 1953	438.4	1971 - 1970	435.2	32	1.50
1953	451.0	1953 - 1952	475.5	1976 - 1975	436.2	33	1.45
1952	500.0	1952 - 1951	447.3	1954 - 1953	438.4	34	1.41
1951	394.6	1951 - 1950	318.7	1952 - 1951	447.3	35	1.37
1950	242.8	1950 - 1949	263.9	1961 - 1960	447.8	36	1.33
1949	285.0	1949 - 1948	354.2	1946 - 1945	450.1	37	1.30
1948	423.5	1948 - 1947	357.8	1970 - 1969	451.9	38	1.26
1947	292.1	1947 - 1946	380.3	1957 - 1956	460.5	39	1.23
1946	468.4	1946 - 1945	450.1	1978 - 1977	464.9	40	1.20
1945	431.9	1945 - 1944	321.5	1953 - 1952	475.5	41	1.17
1944	211.2	1944 - 1943	303.8	1974 - 1973	486.6	42	1.14
1943	396.4	1943 - 1942	328.0	1973 - 1972	501.8	43	1.12
1942	259.5	1942 - 1941	252.6	1956 - 1955	505.8	44	1.09
1941	245.7	1941 - 1940	308.7	1983 - 1982	532.8	45	1.07
1940	371.7	1940 - 1939	397.0	1979 - 1978	540.8	46	1.04
1939	422.3	1939 - 1938	413.1	1984 - 1983	610.2	47	1.02
1938	403.9						

n = 47

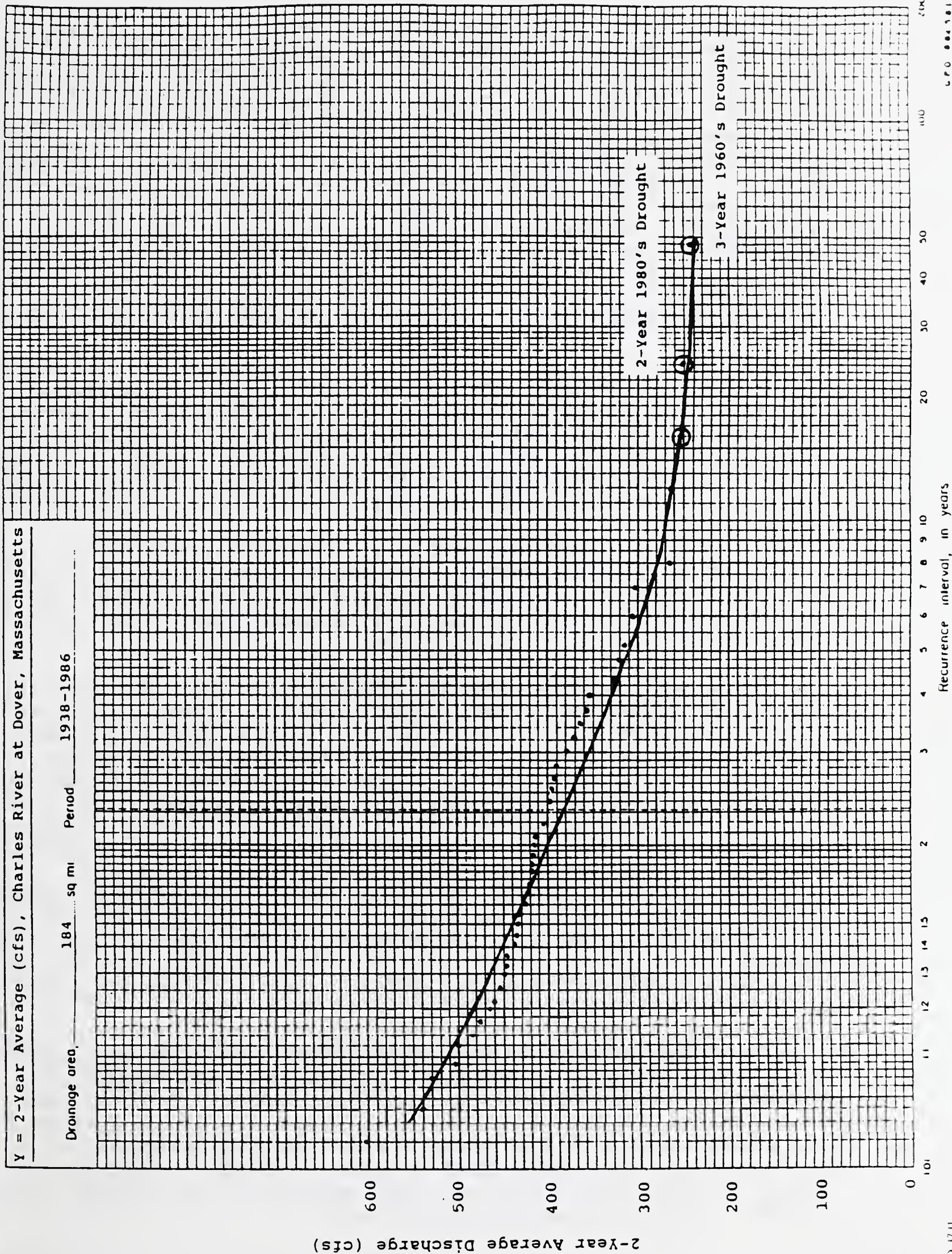
Plot of Recurrence Interval vs. Discharge, Charles River at Dover Gage

Figure 5

File Number

UNITED STATES DEPARTMENT OF THE INTERIOR - GEOLOGICAL SURVEY - WATER RESOURCES DIVISION

9-1790
Flood data plot
(March 1949)



II. SUBBASIN YIELD ANALYSIS (SUBY)

The subbasin yield analysis focuses on the 16 subbasins which comprise the 250 square mile drainage area upstream of the U.S. Geological Survey Streamflow gage #01104500 on the Charles River at Waltham. The subbasins are defined by the major tributary brooks entering the main stem of the Charles River and by subsections of the main stem of the river. The 16 subbasins, in downstream order, are Upper Charles, Hopping Brook, Mine Brook, Chicken Brook, Mill River, Charles River Millis, Stop River, Bogastow Brook, Charles River Medfield, Fuller Brook/Waban, Charles River 128, Charles River Dover, Charles River Wellesley, Rosemary Brook, Stony Brook, Charles River Waltham (Figure 1). Table 3 identifies these subbasins. The urban communities downstream of the Waltham gage are fully supplied by MWRA and not included in this portion of the study.

In the determination of Charles River subbasin yields it is necessary to estimate flow-duration data on streams where long-term gaging station records are not available. When the low-flow end of the duration curve is of prime interest, estimates based on runoff per square mile of nearby gaged areas are seldom reliable unless it is known that the ground water geology of the two areas is similar.

Two methodologies were utilized to determine subbasin yields in the Charles River Basin. The Index Station Method was used in the subbasins upstream of the Dover streamflow gage and the Aquifer Yield Method was employed on subbasins downstream of the Dover gage.

The Index Station Method (Searcy 1959) relates base flow discharge measurements made in the subbasins with concurrent gaged discharges at an index station. This relation is then used to estimate yields in the subbasins based on the long term records at the index station. The relationship is assumed to be most valid for the subbasins contained within the Index Station drainage area. The Aquifer Yield Method was employed for those subbasins downstream of the index station gage. This second methodology utilizes the Chapter 800 Aquifer Yield data calculated for the subbasins of the Charles River Basin (USGS Myette & Simcox 1988). Both methods provide yields based on flow duration curves for the 16 subbasins of the Charles River Basin.

A. Index Station Method (Upstream of Dover gage)

The Index Station Method establishes a relationship between two streamflow gaging stations for a short-term period of concurrent record by plotting the discharges for given baseflow measurements at one station (the subbasin) against discharges at the index station. The index station is the selected streamflow gaging station of continuous long term record. Ideally, the index station should have minimal regulation and should reflect general subbasin geologic conditions.

Table 3

CHARLES RIVER BASIN SUBBASINS

Charles River Basin Subbasins	USGS Streamflow Gage Number Defining Subbasin	Subbasin Drainage Area (sq. mi.)	U.S. Geological Survey Subbasin Delineation Map Index Numbers*
Upper Charles	103200	14.45	20001, 20002, 20003, 20004, 20006, 20007A & B, 20008, 20009, 20010, 20011B
Hopping Brook	103217	10.10	20019B, 20020, 20022, 20023
Mine Brook	103240	14.11	20024, 20025, 20026, 20027, 20029
Chicken Brook	103253	7.23	20030, 20031
Mill River	103300	13.80	20037, 20038, 20039, 20040, 20041
Charles River Millis	103305	24.24	20012, 20013, 20014, 20015, 20016, 20017, 20018, 20032, 20033, 20034, 20035, 20036, 20042, 20043, 20044, 20045, 20046, 20048
Stop River	103330	12.80	20049, 20050, 20051A & B, 20052, 20053
Bogastow Brook	103395	23.43	20057A & B, 20058, 20059, 20060, 20061B, 20062
Charles River, Medfield	103400	20.30	20063, 20064A & B, 20054, 20055, 20056
Fuller Brook	--	15.72	20071, 20072, 20073, 20074, 20075, 20076, 20077, 20078
Charles River, Dover & Natick	103500	26.35	20070C, 20079, 20080, 20081, 20082, 20083, 20084, 20085, 20086
Charles River, Rt. 128	103905	9.07	20087, 20089, 20090, 20091, 20092, 20093A & B
Charles River, Wellesley	104200	19.20	20095, 20097A & B, 20100, 20101
Rosemary Brook	104258	3.87	20102, 20103
Stony Brook	--	23.76	20105, 20106, 20107, 20108, 20110, 20111, 20112, 20113, 20114
Charles River, Waltham	104500	11.72	20104, 20115, 20116, 20118

* From U.S. Geological Survey Report, "Drainage Divides,
Massachusetts River Basins", S. W. Wandle, 1982.

In the subbasins of the Charles River basin, baseflow discharge measurements have been obtained at several sites on various days over the past 25 years. The number of measurements (days of record) varies from approximately 8 measurements to 20 measurements in the various subbasins.

In this analysis, baseflow measuring sites (the drainage areas of these sites define the subbasins) and the index station all are within the index station drainage area. Eleven subbasins have been delineated within the drainage area of the Dover gage, the selected index station. Once a relationship has been established between the index station and the short-term baseflow station, the base flows for various flow durations can be calculated for the subbasin. These values, calculated for the planning drought conditions, provide the subbasin yields.

1. Data Collection

Base flow and other miscellaneous measurements have been collected by the U.S. Geological Survey at numerous locations throughout the Charles River basin (U.S. Geological Survey Miscellaneous Measurements, 1986). Most of these measurements were taken during the late 1960's, the early 1970's, and the mid 1980's to prepare two publications: the Charles River basin Hydrologic Atlas (Walker, 1975) and the USGS report, "Water Resources and Aquifer Yield's in the Charles River Basin"(citation). These measurements are the basis for the Index Station Method for determining subbasin yields. In this analysis, subbasin locations were selected based partially on the number and quality of baseflow measurements at a site. Obviously the more concurrent the streamflow measurements are, the more likely a definable relationship becomes if measured over a range of streamflow discharges.

2. Demand Adjustment

Once the baseflow measurements were obtained from the USGS, the next step in determining flow relationships was to make appropriate adjustments based on demand. In the Charles River basin, human use has altered the baseflow values. Index and baseflow station streamflow measurements have been adjusted to reflect virgin streamflow conditions prior to correlating the data. This insures the best possible correlation, as would exist under pre-demand conditions. The streamflow data used in this study was adjusted on a seasonal basis for the three data gathering periods mentioned above (late 1960's, early 1970's, mid 1980's). The index station daily flows were adjusted to reflect natural conditions as well. In both instances streamflow measurements were adjusted by varying amounts depending on the year, the season the measurements were taken, and the volume of demand.

During summer months, when the majority of the base flow measurements were made, the out-of-subbasin loss is significantly greater than in late summer and fall seasons which

are the hydrologically low flow periods. Also, adjustments were generally greater in the late 1960's and early 1970's than in the 1982-83 period due, primarily, to the water supply operation of the towns of Natick and Needham. Natick has relied less on Charles River basin sources since large wellfields were developed in the Concord River basin during the mid 1970's. Needham relied more heavily on MWRA during summer months in the early 1980's, than on Charles River basin sources. Exact daily adjustments could not be made due to the lack of data on pumping and return flows. There is a lag time between pumping and its measurable effect on streamflow. Incorporating this relationship may make the seasonal adjustments used in this study a more accurate procedure than adjustments based on concurrent daily pumping and returns.

The inflows and outflows in each subbasin have been determined seasonally for each of the 16 subbasins as well as for the index station. Summer (1988) demand and return adjustments are detailed in a later section of this report (Subbasin Withdrawals and Wastewater Discharges). This same methodology was employed with the appropriate data for inflows and outflows as they existed during the months in which the baseflow measurements were taken. Changes have occurred in the basin and subbasins in terms of new reservoirs, wells, and sewage treatment plants since the late 1960's, all of which have been taken into consideration when adjusting the streamflow data.

3. Data Quality Control

To ensure a valid correlation between the baseflow and the index stations, it was assumed that streamflow conditions in the subbasin and the index station subbasin are as close to baseflow conditions as possible. Baseflows are low flows which are predominantly comprised of ground water infiltration and occur after periods of minimal precipitation and subsequent runoff. Data from two Water Resources Commission precipitation stations were used to verify the existence of base flow conditions on the day of streamflow record. Daily precipitation records for the years 1967-1971 and 1982-1983 from station no. 728 (town of Franklin) and no. 716 (Needham, Charles River pumping station) were used (Figure 6).

Verifying baseflow measurements requires two determinations: the amount of precipitation which would have a discernible effect on the streamflow measurements and, second, after a precipitation event, how long it will take before the flows at the measuring point return to baseflow conditions. The US Geological Survey was consulted pertaining to procedures and data analysis of low flow measurements (Rigas 1972). It is assumed that for small subbasins, isolated precipitation events of 10/100th of an inch or less a few days prior to baseflow measurements have minimal effect on streamflow. This assumption has been verified by comparing the precipitation records and the streamflow records at the index station.

WATER RESOURCES COMMISSION

100 CAMBRIDGE STREET, BOSTON 02202

PRECIPITATION REPORT

Station Town of Franklin Water Dept.For the month of JULY 19 69

	DAY OF MONTH	TIME OF BEGINNING	TIME OF ENDING	AMOUNT	REMARKS
	1				
	2				
	3	during nite			
	4			.18	showers
	5		Early Morn.	.07	showers
	6				
	7				
	8				
	9				
	10				
	11				
	12	during Day			
	13	~~rain~~		1.47	Rain
	14		Early Morn.	.58	Rain
	15				
	16				
	17				
	18				
	19	During Nite			
	20			.11	Rain
	21			.11	Shower
	22	EARLY MORN.	Mid Morning	.25	SHOWERS
	23				
	24				
	25				
	26				
	27				
	28	during nite	cont.	.35	Shower
	29		"	.32	"
	30		mid Nite	1.10	"
	31			.42	"

TOTAL

4.76 ✓

Matthew Fontaine Observer

Note. — If precipitation is in form of snow, state amount in water, and also under "Remarks" the actual depth in inches.

SEND WHITE SHEET TO THE OFFICE THE FIRST OF EACH MONTH

A second analysis was done to determine the flow response time of a significant precipitation event at the index station. A series of independent rainfall events were compared with corresponding flows at the Charles River Dover index gage station. The events examined occurred during the low flow time of year. Ambient conditions in the winter/spring are different than in the summer/fall (i.e., higher ground water levels, snowfall vs. rainfall, snowmelt, etc.) and will result in a different response time. The data (Figure 7) indicate that after an isolated precipitation event during low flow months, it takes six to eight days for the river flow at the index station to return back to baseflow levels. In the subbasins examined in the Charles River Basin, it is assumed that the response period would be significantly shorter than the 6-8 days of the index station. Therefore, baseflow conditions will not be achieved concurrently at the subbasin and at the index station until at least six days after a significant rainfall event.

The baseflow measurements taken in the various subbasins were examined and compared with the associated precipitation records. Measurements which occurred within six days of a precipitation event and measured over 10/100ths of an inch were discarded. Flow measurements which occurred 8 or more days after an event were considered to be highly reflective of baseflow conditions at both the subbasin and the index station. Also any measurements taken in moderate or high flow months were rejected because the relationship at higher flows can be radically different than during low flow periods.

4. Baseflow Station to Index Station Correlation

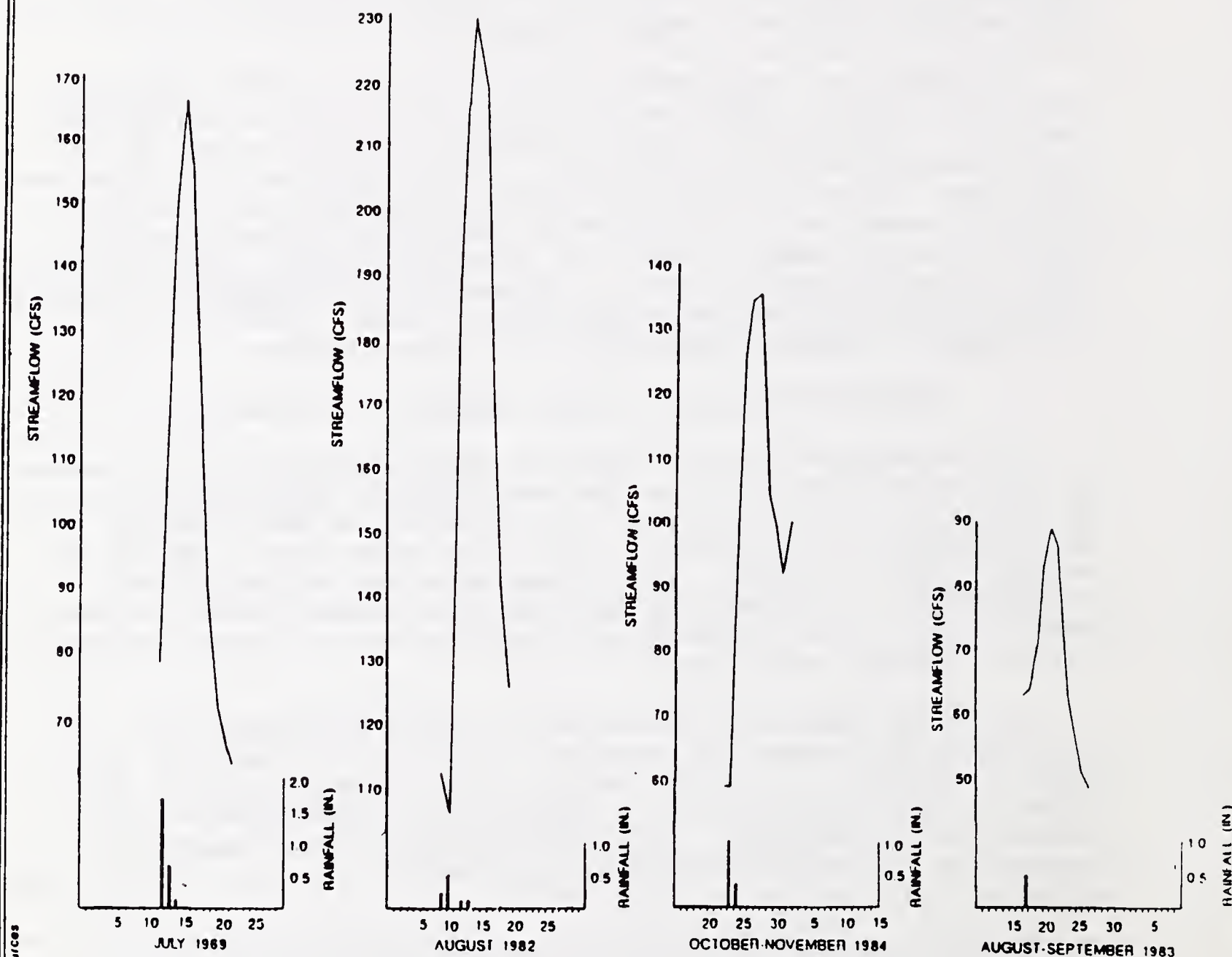
The effect of basin geology on streamflow can be evaluated by analyzing several discharge measurements made during periods of base flow. The discharge measurements at the baseflow observation point preferably should be made over a period of several years; however, regardless of when they are made, estimates of low flow based on baseflow measurements are much more reliable than those based strictly on the runoff per square mile of nearby gaged areas.

The development of the equation which expresses the relationship between the subbasin and the index station is a complex process. It involves not only the analysis of the effect of precipitation on streamflow but also the effect of geology on streamflow. Once a statistical relationship is developed it can then be used to establish the low flows in the ungaged subbasin.

In the Charles River basin, those ungaged sites are the Upper Charles, Hopping Brook, Mine Brook, Chicken Brook, Mill River, Charles River Millis, Stop River, Bogastow Brook, Charles River Medfield, and Fuller/Waban Brook (Figures 8-17). The index station is the Charles River at Dover gage (Figure 18). For most subbasins, the measurements group near the lower end of the curve of relations, and lines of various slopes could be drawn to average the group of measurements. The measurements

Figure 7

Examples of Streamflow Response to Precipitation Events at the Charles River, Dover



serve to fix the location of a line of relation (regression line) but not the slope. To insure the best possible fit of the line, discharge measurements have been assigned different weights based on the quality of the data used in the regression analysis. By assigning different weights to the data, based on its reliability, the bias introduced using regression analysis should be minimal. Measurements which were taken within six or seven days of a significant precipitation event or data that has one or more minor precipitation event (less than 10/100ths of an inch) within eight or more days of a major precipitation event were assigned a single weight. Data which fell in the category considered to be highly reflective of baseflow conditions (8 days or more of no precipitation) were assigned a double weight. By following the above criteria, the location of the lower end of the regression curve can be fixed for each ungaged subbasin (Figures 8-18).

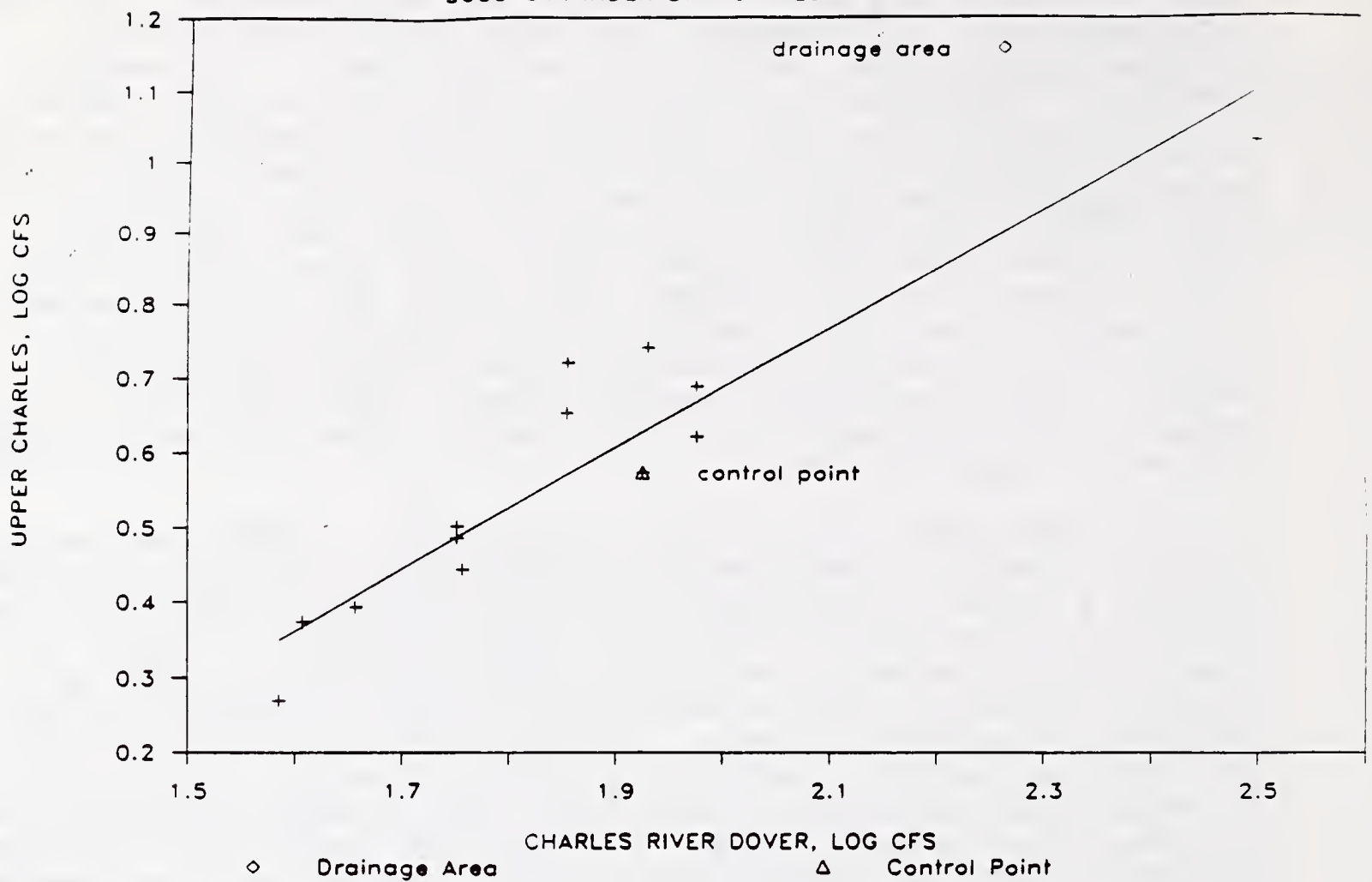
The characteristics of the relationship between the weighted subbasin discharge measurements and the gaging station records furnish a basis for fitting the curve of relation when only the position of the curve at the lower end is known. A line of equal-yield (drainage area ratio) drawn through the plot of the subbasin drainage area to the index station drainage area serves as a guide for this purpose. For many streams, the high end of the curve of relation tends to parallel or merge with the line of equal yield because at high flow, storm runoff predominates and base flow is negligible. However, the regression curve of relation diverges from the equal yield line at low flow because the curve is affected primarily by the geology of the drainage areas (Searcy, 1959).

To better represent the actual slope of the line of relation under baseflow conditions the plot of areas of stratified drift (sand and gravel) is used in place of the drainage area ratio. The areas of stratified drift affect the subbasin flows significantly in times of low flow. A subbasin with a large percentage of drainage area in sand and gravel will have relatively high baseflow values. A subbasin with small amounts of sand and gravel and a high percentage of till will tend to have relatively low baseflow values. Thus, the curve of relation will deviate from the line of equal-yield toward the sand and gravel ratio plot. In the development of the curve of relation, the plot of the area of sand and gravel of the subbasin to the area of sand and gravel of the index station is given a triple weight in the regression analysis. When one basin, either the subbasin or the index station basin, contains enough storage, either on the surface or in the ground, to distribute the effect of the storm precipitation over a period of time, and the other basin contains comparatively little storage, the upper end of the line of relation may deviate away from the plot of stratified drift ratios. Although this factor is beyond the scope of this study, storage may account for some discrepancies in the slopes of some of the regression curves developed.

Figure 8

UPPER CHARLES/CHARLES RIVER, DOVER

SUBBASIN/INDEX STATION FLOW CORRELATION



UPPER CHARLES			CHARLES RIVER AT DOVER				
Subbasin			Index Station				
-----			-----				
DATE OF MEASUREMENT	ADJUSTED	LOG	:	ADJUSTED	LOG	:	RESULT OF REGRESSION ANALYSIS
	DISCHARGE	ADJUSTED	:	DISCHARGE	ADJUSTED	:	
	(CFS)	DISCHARGE	:	(CFS)	DISCHARGE	:	
-----			-----			-----	
8-24-67	4.50	0.653	:	71	1.853	:	
9-07-67	4.90	0.690	:	94	1.975	:	R Squared 0.847
10-02-68*	1.86	0.270	:	38	1.585	:	
10-18-68*	2.36	0.373	:	40	1.607	:	Regression
5-28-69	10.87	1.036	:	317	2.502	:	Line Equation:
7-10-69	3.16	0.500	:	56	1.751	:	Y = 0.824(X) - 0.957
9-17-69	4.18	0.621	:	94	1.975	:	
10-31-69*	5.27	0.722	:	71	1.854	:	
7-29-70*	3.05	0.484	:	56	1.751	:	
9-14-70	2.47	0.393	:	45	1.656	:	
8-24-82	5.55	0.744	:	85	1.929	:	
9-13-82	2.77	0.442	:	57	1.756	:	
			:			:	
control point	3.74	0.573	:	84	1.924	:	

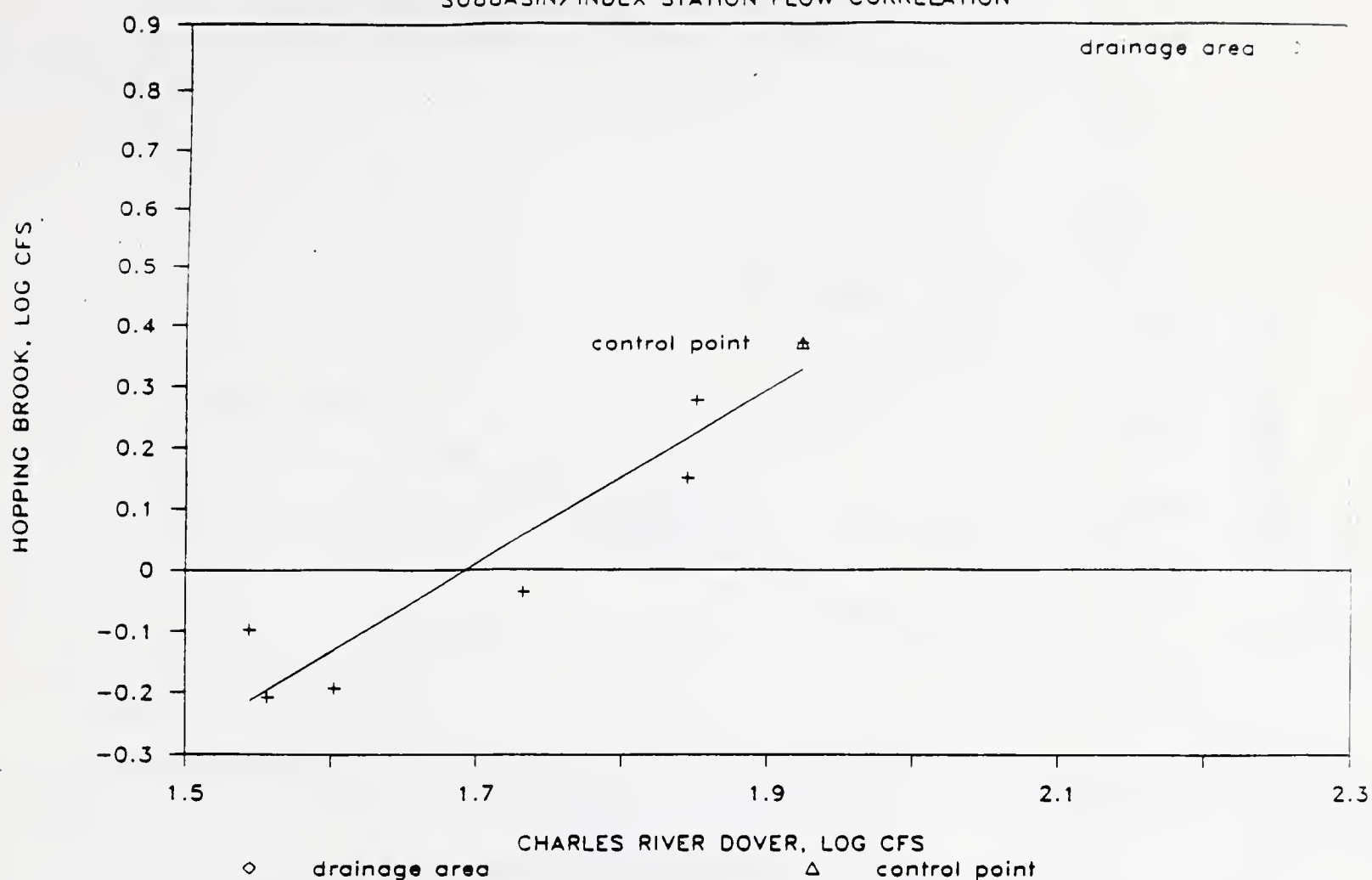
* Double Weighted

Basin	Drainage Area (sm)	Sand and Gravel Area (sm)
Upper Charles	14.5	3.7
Charles, Dover	184.0	84.0

Figure 9

HOPPING BROOK/CHARLES RIVER, DOVER

SUBBASIN/INDEX STATION FLOW CORRELATION



HOPPING BROOK			:	CHARLES RIVER AT DOVER		:		
Subbasin			:	Index Station		:		
-----			:	-----		:		
DATE OF	ADJUSTED	LOG	:	ADJUSTED	LOG	:	RESULT OF	
MEASUREMENT	DISCHARGE	ADJUSTED	:	DISCHARGE	ADJUSTED	:	REGRESSION ANALYSIS	
	(CFS)	DISCHARGE	:	(CFS)	DISCHARGE	:		
-----			:	-----		:	-----	
8-30-68*	0.80	-0.097	:	35	1.544	:		
9-24-68*	0.64	-0.194	:	40	1.602	:	R Squared	0.902
10-03-68*	0.62	-0.208	:	36	1.556	:		
07-11-69*	0.92	-0.036	:	54	1.732	:	Regression	
09-25-69*	1.41	0.149	:	70	1.845	:	Line Equation:	
10-31-69*	1.90	0.279	:	71	1.851	:	Y = 1.429(X) - 2.419	
			:			:		
control point	2.37	0.375	:	84	1.924	:		

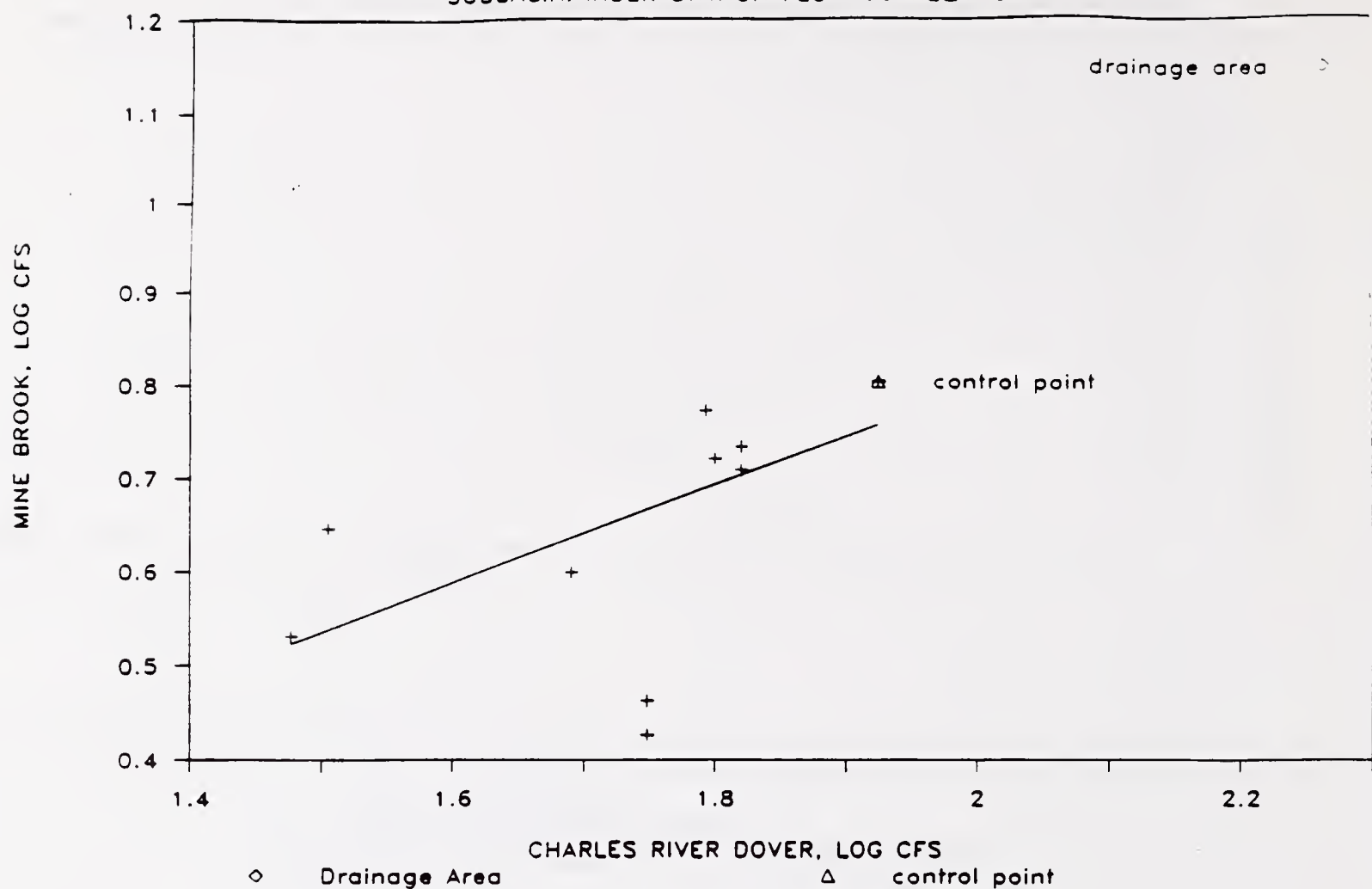
* Double Weighted

Basin	Drainage Area (sm)	Sand and Gravel Area (sm)
Hopping Brook	7.3	2.4
Charles River	184.0	84.0

Figure 10

MINE BROOK/CHARLES RIVER DOVER

SUBBASIN/INDEX STATION FLOW CORRELATION



DATE OF MEASUREMENT	MINE BROOK Subbasin		:	CHARLES RIVER AT DOVER Index Station		:	RESULT OF REGRESSION ANALYSIS
	ADJUSTED DISCHARGE (CFS)	LOG ADJUSTED DISCHARGE	:	ADJUSTED DISCHARGE (CFS)	LOG ADJUSTED DISCHARGE	:	
09-24-68*	4.41	0.644	:	32	1.505	:	R Squared 0.373 Regression Line Equation: $Y = 0.529(X) - 0.259$
10-02-68*	3.39	0.530	:	30	1.477	:	
07-10-69	2.90	0.462	:	56	1.748	:	
09-17-69*	6.39	0.806	:	84	1.924	:	
09-25-69*	5.94	0.774	:	62	1.792	:	
10-31-69*	5.26	0.721	:	63	1.799	:	
07-29-70*	2.67	0.427	:	56	1.748	:	
08-12-70	3.97	0.599	:	49	1.690	:	
08-17-83	5.42	0.734	:	66	1.820	:	
08-24-83	5.12	0.709	:	66	1.820	:	
control point	6.40	0.806	:	84	1.924	:	

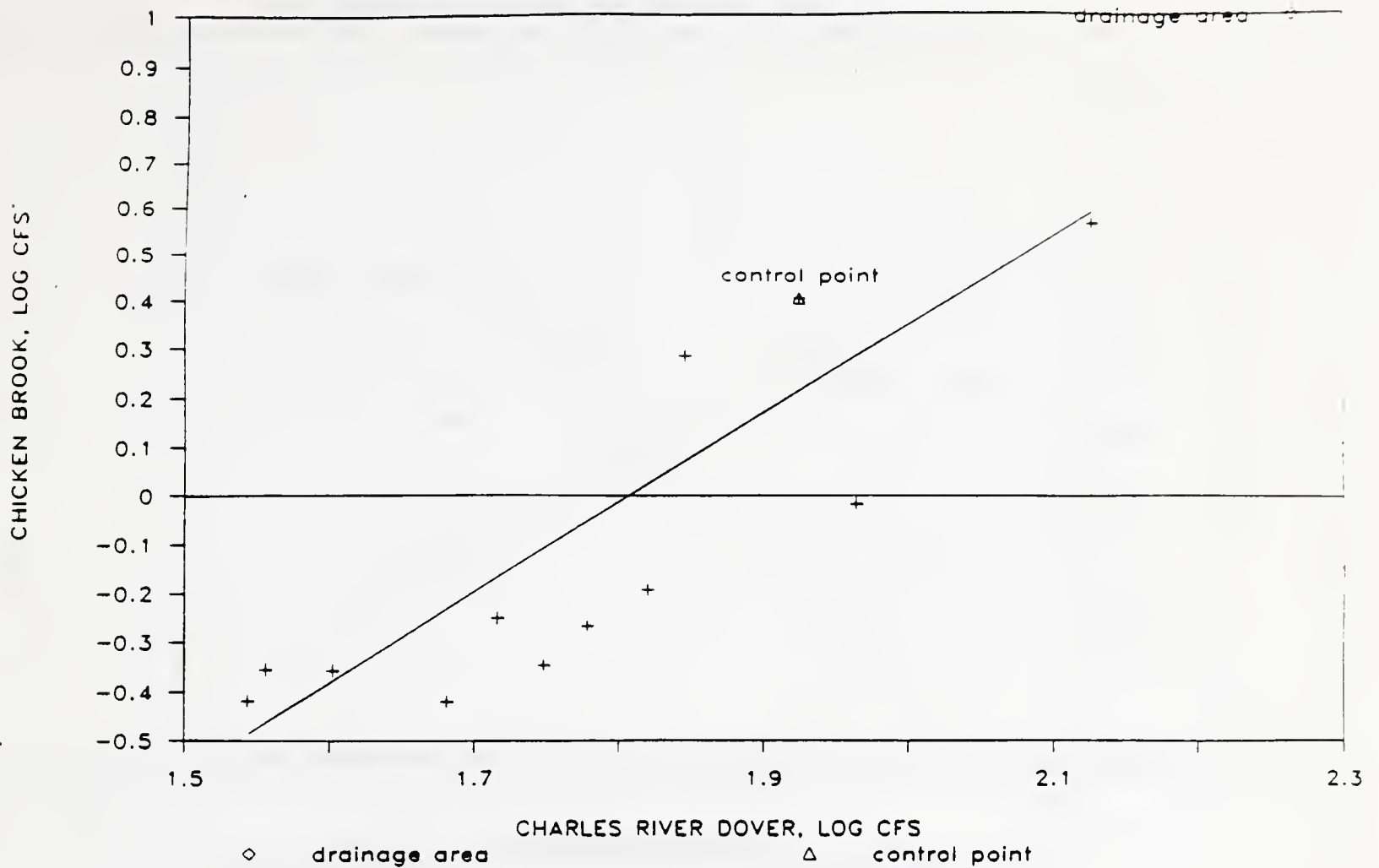
* Double Weighted

Basin	Drainage Area (sm)	Sand and Gravel Area (sm)
Mine Brook	14.1	6.4
Charles River	184.0	84.0

Figure 11

CHICKEN BROOK/CHARLES RIVER DOVER

SUBBASIN/INDEX STATION FLOW CORRELATION



CHICKEN BROOK			:	CHARLES RIVER AT DOVER		:		
Subbasin			:	Index Station		:		
-----			:	-----		:		
DATE OF	DISCHARGE	LOG	:	ADJUSTED	LOG	:	RESULT OF	
MEASUREMENT	(CFS)	DISCHARGE	:	DISCHARGE	ADJUSTED	:	REGRESSION ANALYSIS	
			:	(CFS)	DISCHARGE	:		
-----			:	-----		:		
08-30-68*	0.38	-0.420	:	35	1.544	:		
09-24-68*	0.44	-0.357	:	40	1.602	:	R Squared	0.794
10-03-68	0.44	-0.357	:	36	1.556	:		
07-10-69	0.45	-0.347	:	56	1.748	:	Regression	
09-17-69	0.96	-0.018	:	92	1.964	:	Line Equation:	
09-25-69*	1.94	0.288	:	70	1.845	:	Y = 1.849(X) - 3.340	
06-24-83*	3.7	0.568	:	134	2.127	:		
07-19-83	0.56	-0.252	:	52	1.716	:		
08-10-83	0.38	-0.420	:	48	1.681	:		
08-17-83	0.64	-0.194	:	66	1.820	:		
08-25-83	0.54	-0.268	:	60	1.778	:		
			:			:		
control point	2.58	0.412	:	84	1.924	:		

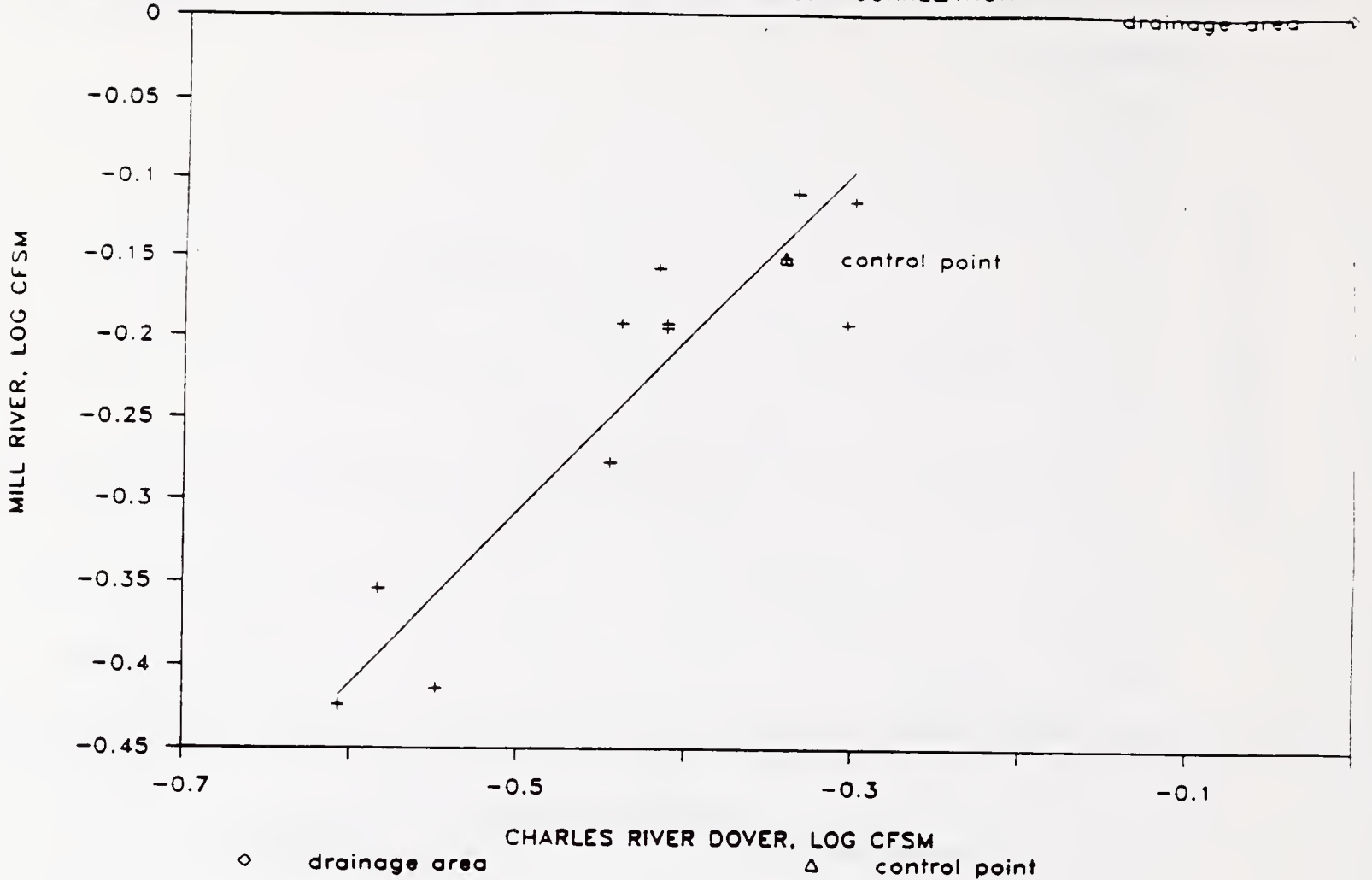
* Double Weighted

Basin	Drainage Area (sm)	Sand and Gravel Area (sm)
Chicken Brook	10.0	2.6
Charles River	184.0	84.0

Figure 12

MILL RIVER/CHARLES RIVER, DOVER

SUBBASIN/INDEX STATION FLOW CORRELATION



MILL RIVER Subbasin				CHARLES RIVER Index Station			RESULT OF REGRESSION ANALYSIS		
LOG				LOG					
DATE OF MEASUREMENT	ADJUSTED DISCHARGE (CFS)	DISCHARGE PER SQR MILE	DISCHARGE PER SQR MILE	ADJUSTED DISCHARGE (CFS)	DISCHARGE PER SQR MILE	DISCHARGE PER SQR MILE			
08-24-67*	4.5	0.643	-0.192	71	0.388	-0.412			
09-07-67	4.5	0.643	-0.192	92	0.497	-0.303	R Squared	0.872	
07-11-83	4.5	0.643	-0.192	67	0.364	-0.439			
07-19-83*	2.7	0.386	-0.414	52	0.283	-0.549	Equation of		
08-10-83	3.1	0.443	-0.354	48	0.261	-0.584	Regression Line:		
08-17-83	3.7	0.529	-0.277	66	0.359	-0.445	Y = 1.047(X) + 0.217		
08-24-83	3.7	0.529	-0.277	66	0.359	-0.445			
08-24-67	6.9	0.639	-0.195	71	0.388	-0.412			
09-08-67*	8.4	0.778	-0.109	86	0.465	-0.333			
09-17-69	10.6	0.768	-0.115	93	0.503	-0.299			
09-25-69*	9.6	0.696	-0.158	71	0.383	-0.417			
10-08-70*	5.2	0.377	-0.424	46	0.247	-0.607			
control point	9.78	0.709	-0.150	84	0.457	-0.341			
							Basin	Drainage Area (sm)	Sand and Gravel Area (sm)
							Mill River	13.8	9.8
							Charles River Dover	184.0	84.0
							Eagle Brook	7.0	--
							City Mills	10.8	--

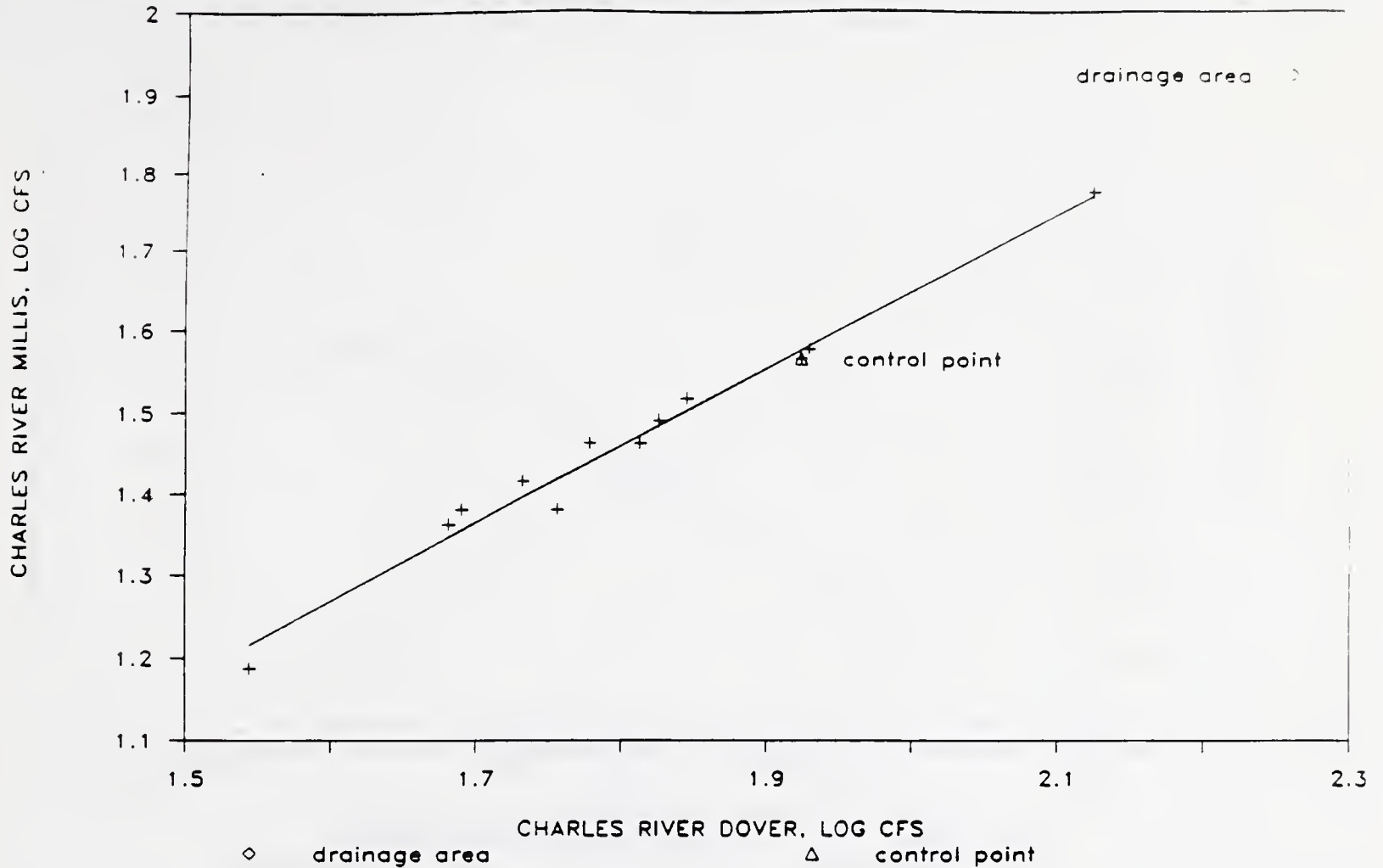
*Double Weighted

*Double Weighted

Figure 13

CHARLES R. MILLIS/CHARLES RIVER, DOVER

SUBBASIN/INDEX STATION FLOW CORRELATION

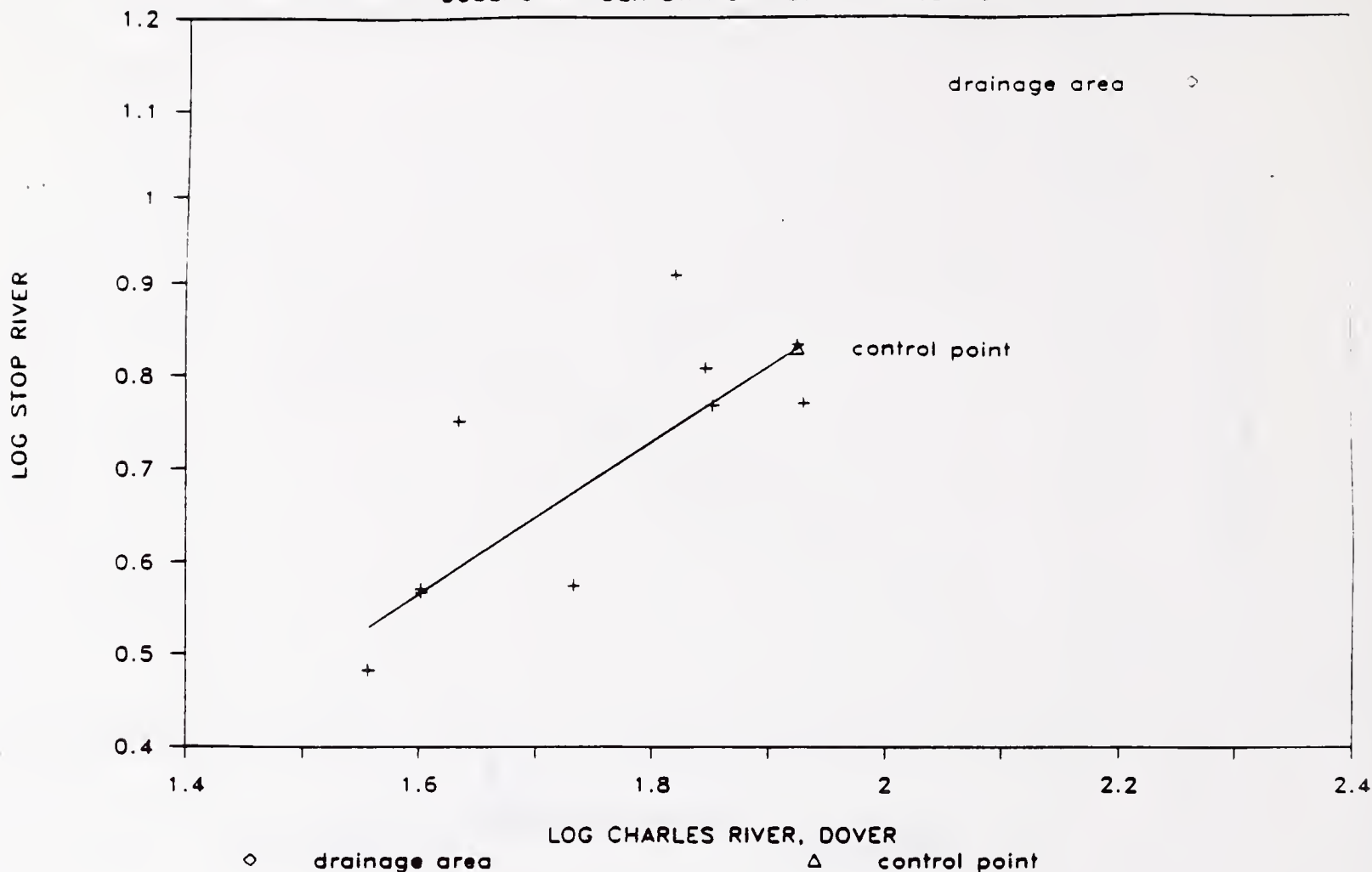


CHARLES RIVER AT MILLIS			:	CHARLES RIVER AT DOVER			:
Subbasin			:	Index Station			:
			:				:
DATE OF MEASUREMENT	ADJUSTED	LOG	:	ADJUSTED	LOG	:	RESULT OF REGRESSION ANALYSIS
	DISCHARGE (CFS)	ADJUSTED DISCHARGE	:	DISCHARGE (CFS)	ADJUSTED DISCHARGE	:	
08-30-68	15	1.188	:	35	1.544	:	R Squared 0.981 Regression Line Equation: $Y = 0.957(X) - 0.264$
08-24-82	38	1.580	:	85	1.929	:	
08-30-82	33	1.519	:	70	1.845	:	
09-10-82	29	1.462	:	65	1.813	:	
09-13-82	24	1.380	:	57	1.756	:	
06-24-83	60	1.778	:	134	2.127	:	
07-11-83	31	1.491	:	67	1.826	:	
07-20-83	24	1.380	:	49	1.690	:	
08-10-83	23	1.362	:	48	1.681	:	
08-25-83	29	1.462	:	60	1.778	:	
08-26-83	26	1.415	:	54	1.732	:	
			:			:	
control point	37	1.568	:	84	1.924	:	

Basin	Drainage Area (sm)	Sand and Gravel Area (sm)
Charles River Millis	84.0	37.0
Charles River Dover	184.0	84.0

Figure 14 STOP RIVER/CHARLES RIVER, DOVER

SUBBASIN/INDEX STATION FLOW CORRELATION



STOP RIVER			:	CHARLES RIVER AT DOVER		:		
Subbasin			:	Index Station		:		
-----			:	-----		:		
DATE OF MEASUREMENT	ADJUSTED	LOG	:	ADJUSTED	LOG	:	RESULT OF	
	DISCHARGE	ADJUSTED	:	DISCHARGE	ADJUSTED	:	REGRESSION ANALYSIS	
	(CFS)	DISCHARGE	:	(CFS)	DISCHARGE	:	-----	
08-24-67	5.87	0.769	:	71	1.851	:		
09-08-67*	5.91	0.772	:	85	1.929	:	R Squared	0.703
09-25-68	3.68	0.566	:	40	1.602	:		
10-03-68*	3.04	0.483	:	36	1.556	:	Regression	
10-16-68	5.63	0.751	:	43	1.633	:	Line Equation:	
07-11-69*	3.74	0.573	:	54	1.732	:	Y = 0.827(X) - 0.760	
09-25-69*	6.44	0.809	:	70	1.845	:		
10-12-70	3.71	0.569	:	40	1.602	:		
08-24-83	8.2	0.914	:	66	1.820	:		
			:			:		
control point	6.86	0.836	:	84	1.924	:		

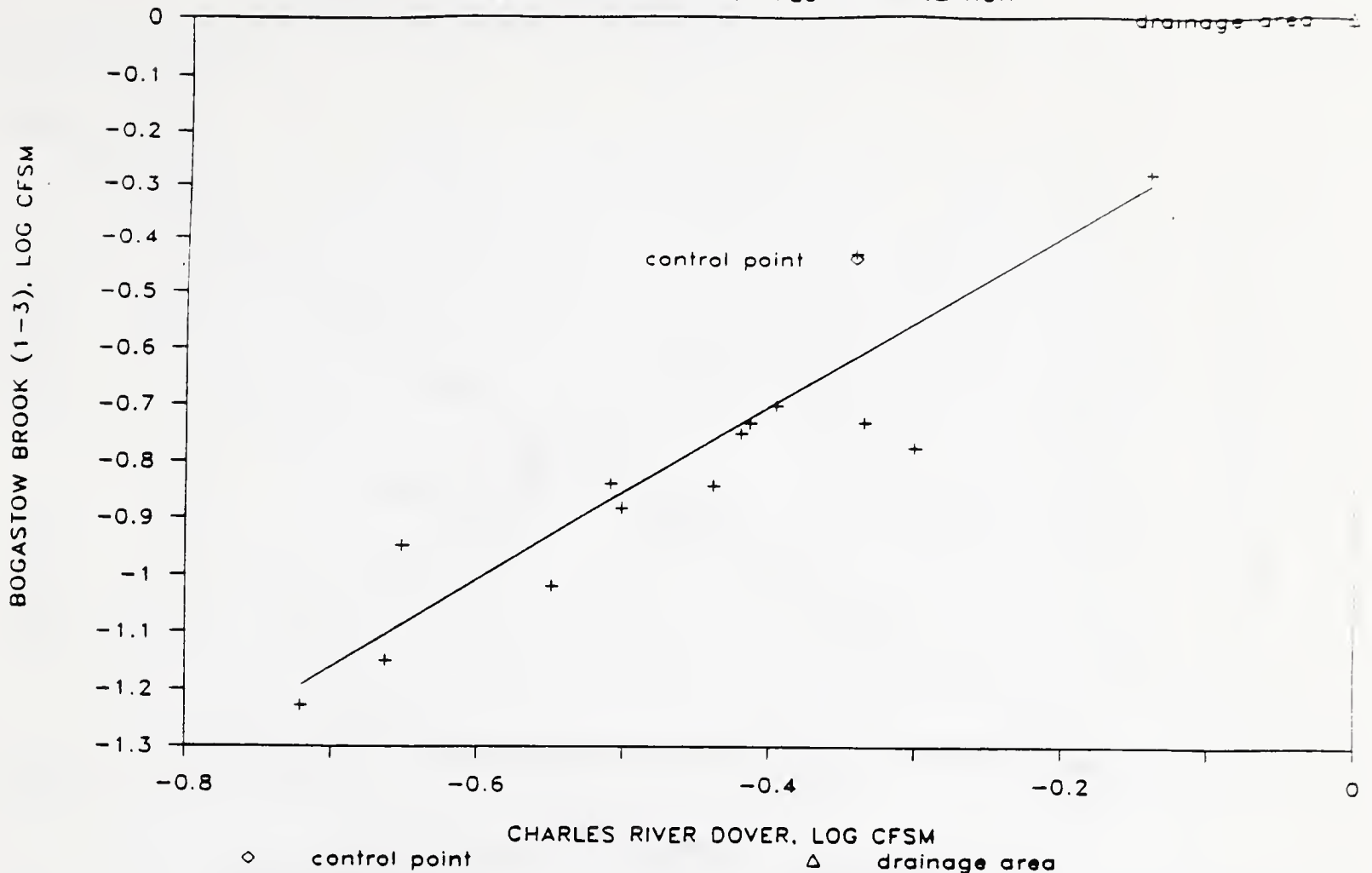
*Double Weighted

Basin	Drainage Area (sm)	Sand and Gravel Area (sm)
Stop River	13.5	6.8
Charles River	184.0	84.0

Figure 15

BOGASTOW BROOK/CHARLES RIVER, DOVER

SUBBASIN/INDEX STATION FLOW CORRELATION



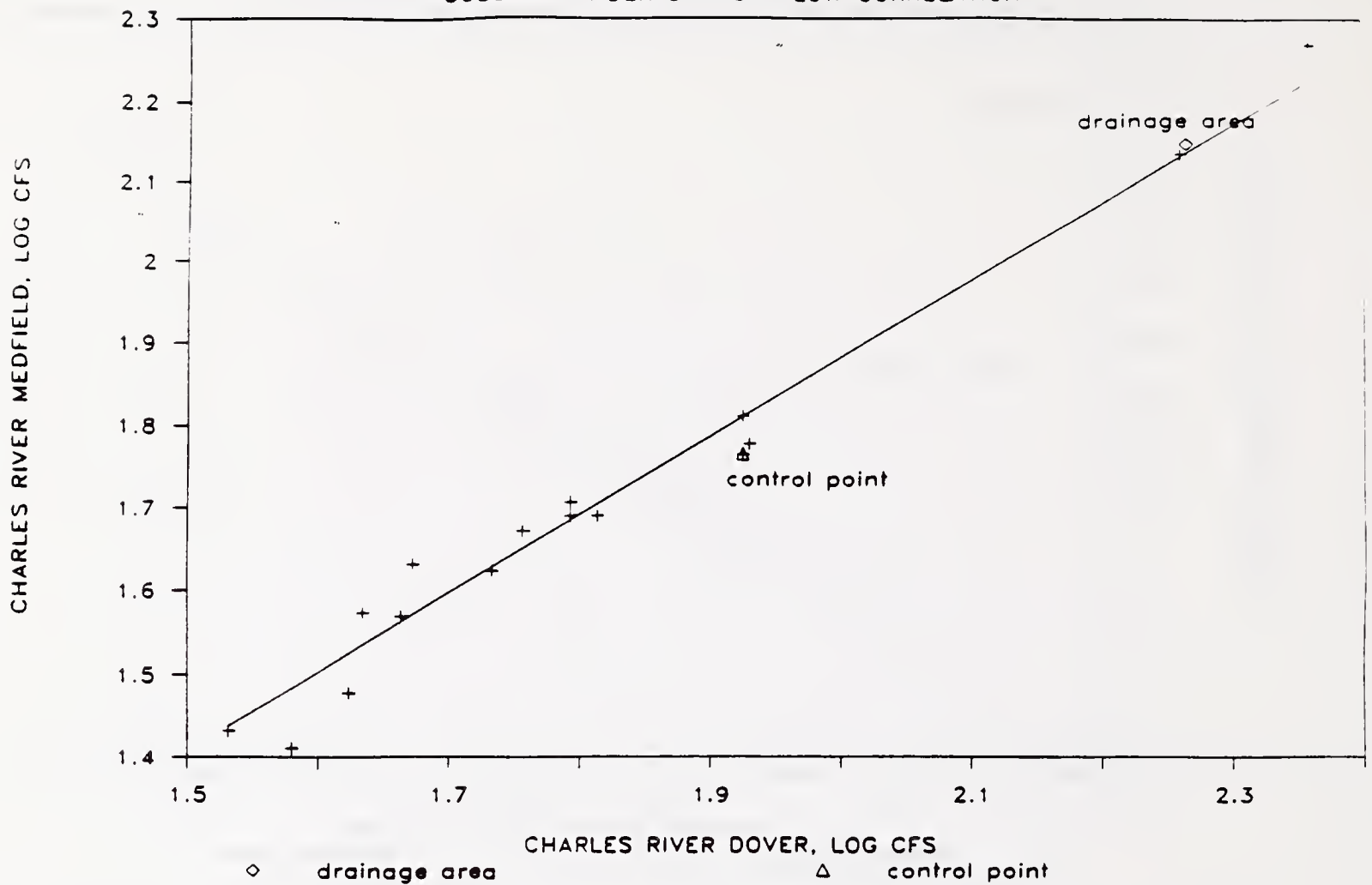
BOGASTOW BROOK (1),(2),(3)				CHARLES RIVER AT DOVER					
Subbasin				Index Station					
LOG				LOG					
ADJUSTED DISCHARGE DISCHARGE				ADJUSTED DISCHARGE DISCHARGE				RESULT OF	
DATE OF	DISCHARGE PER SQR	PER SQR		DISCHARGE PER SQR	PER SQR			REGRESSION ANALYSIS	
MEASUREMENT	(CFS)	MILE	MILE	(CFS)	MILE	MILE			
08-24-67 (1)	4.35	0.186	-0.731	71	0.386	-0.414			
09-08-67* (1)	4.36	0.186	-0.730	85	0.462	-0.335	R Squared	0.854	
06-24-83* (2)	11.00	0.526	-0.279	134	0.728	-0.138			
07-11-83 (2)	3.00	0.144	-0.843	67	0.364	-0.439	Regression		
07-19-83 (2)	2.00	0.096	-1.019	52	0.283	-0.549	Line Equation:		
08-30-68* (3)	0.77	0.059	-1.227	35	0.190	-0.721	$Y = 0.1532(X) - 0.088$		
09-24-68* (3)	0.92	0.071	-1.150	40	0.217	-0.663			
10-17-68* (3)	1.46	0.112	-0.950	41	0.223	-0.652			
07-09-69 (3)	1.88	0.145	-0.840	57	0.310	-0.509			
09-17-69 (3)	2.19	0.168	-0.773	92	0.500	-0.301	Drainage Sand & Gravel		
09-25-69* (3)	2.31	0.178	-0.750	70	0.380	-0.420	Basin Area (sm)	Area (sm)	
10-30-69* (3)	2.60	0.200	-0.699	74	0.402	-0.396			
07-28-70 (3)	1.70	0.131	-0.883	58	0.315	-0.501	Bogastow Brook		
							(1) (Orchard St.)	23.4	8.83
control point	8.83	0.38	-0.423	84	0.46	-0.341	(2) (Below Great		
							Black Swamp)	20.9	---
							(3) (Near Millis)	13.0	---
							Charles River		
							at Dover	184.0	84.0

* Double Weighted

Figure 16

CHARLES R. MEDFIELD/CHARLES RIVER DOVER

SUBBASIN/INDEX STATION FLOW CORRELATION

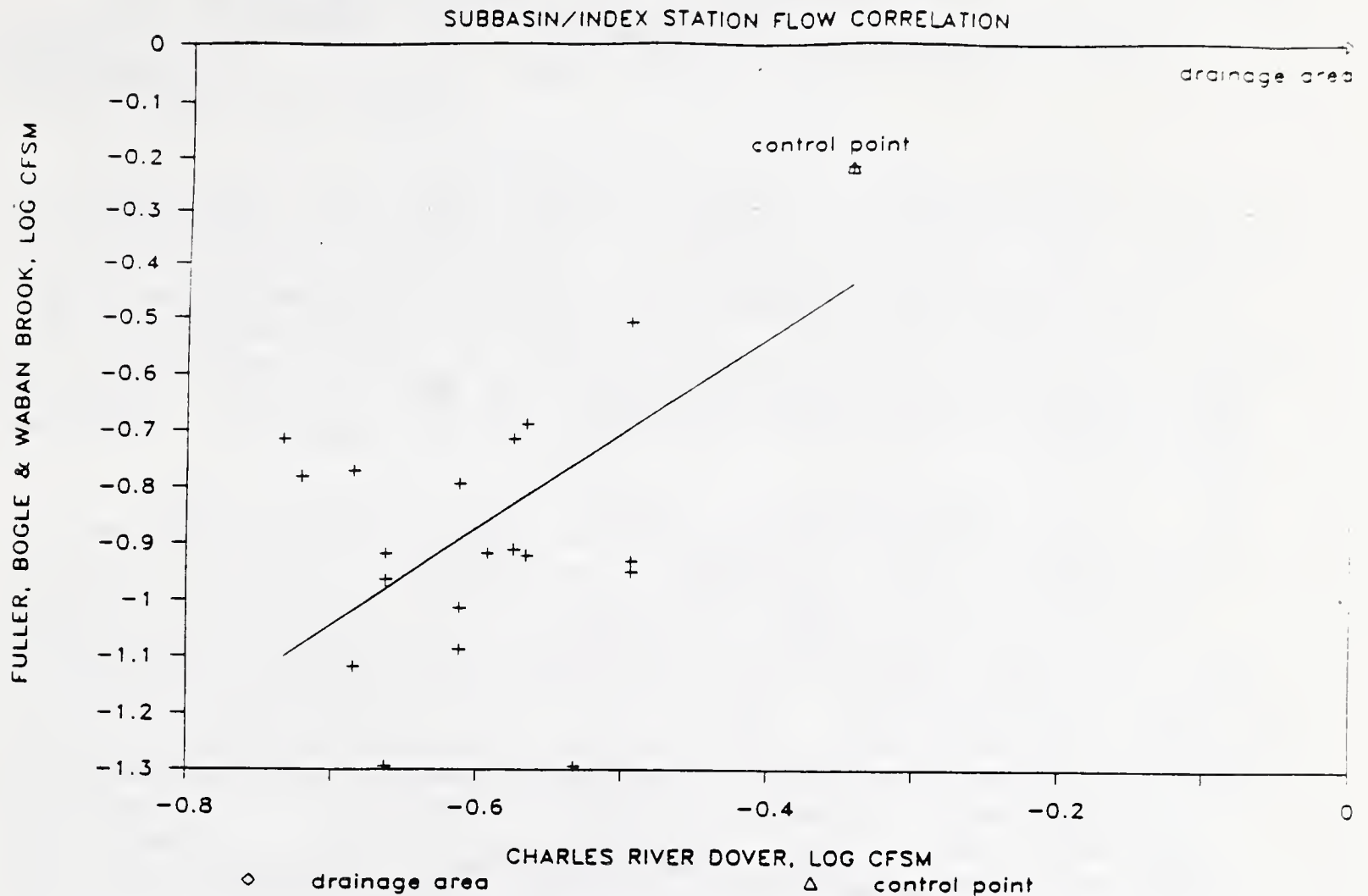


CHARLES RIVER, MEDFIELD Subbasin			CHARLES RIVER AT DOVER Index Station		RESULT OF REGRESSION ANALYSIS
DATE OF MEASUREMENT	ADJUSTED DISCHARGE (CFS)	LOG ADJUSTED DISCHARGE	ADJUSTED DISCHARGE (CFS)	LOG ADJUSTED DISCHARGE	
06-03-69	186	2.270	229	2.360	R Squared 0.965
07-11-69*	37	1.573	43	1.633	Regression Line Equation: $Y = 0.951(X) - 0.019$
09-17-69	65	1.812	84	1.924	
09-25-69*	51	1.707	62	1.792	
07-28-70*	43	1.631	47	1.672	Basin Drainage Sand and Area (sm) Gravel Area (sm) Charles River at Medfield 140.4 58.3 Charles River at Dover 184.0 84.0 Charles River Medfield, Subbasin 19.6 9.2
08-12-70	26	1.410	38	1.580	
08-26-70	136	2.134	182	2.260	
09-14-70	27	1.431	34	1.531	
08-25-82	60	1.778	85	1.929	
08-31-82	49	1.690	65	1.813	
09-10-82*	49	1.690	62	1.792	
09-13-82*	42	1.623	54	1.732	
09-20-82	30	1.477	42	1.623	
07-20-83*	37	1.568	46	1.663	
08-25-83	47	1.672	57	1.756	
control point	58.3	1.766	84	1.924	

* Double Weighted

Figure 17

FULLER & WABAN / CHARLES RIVER DOVER



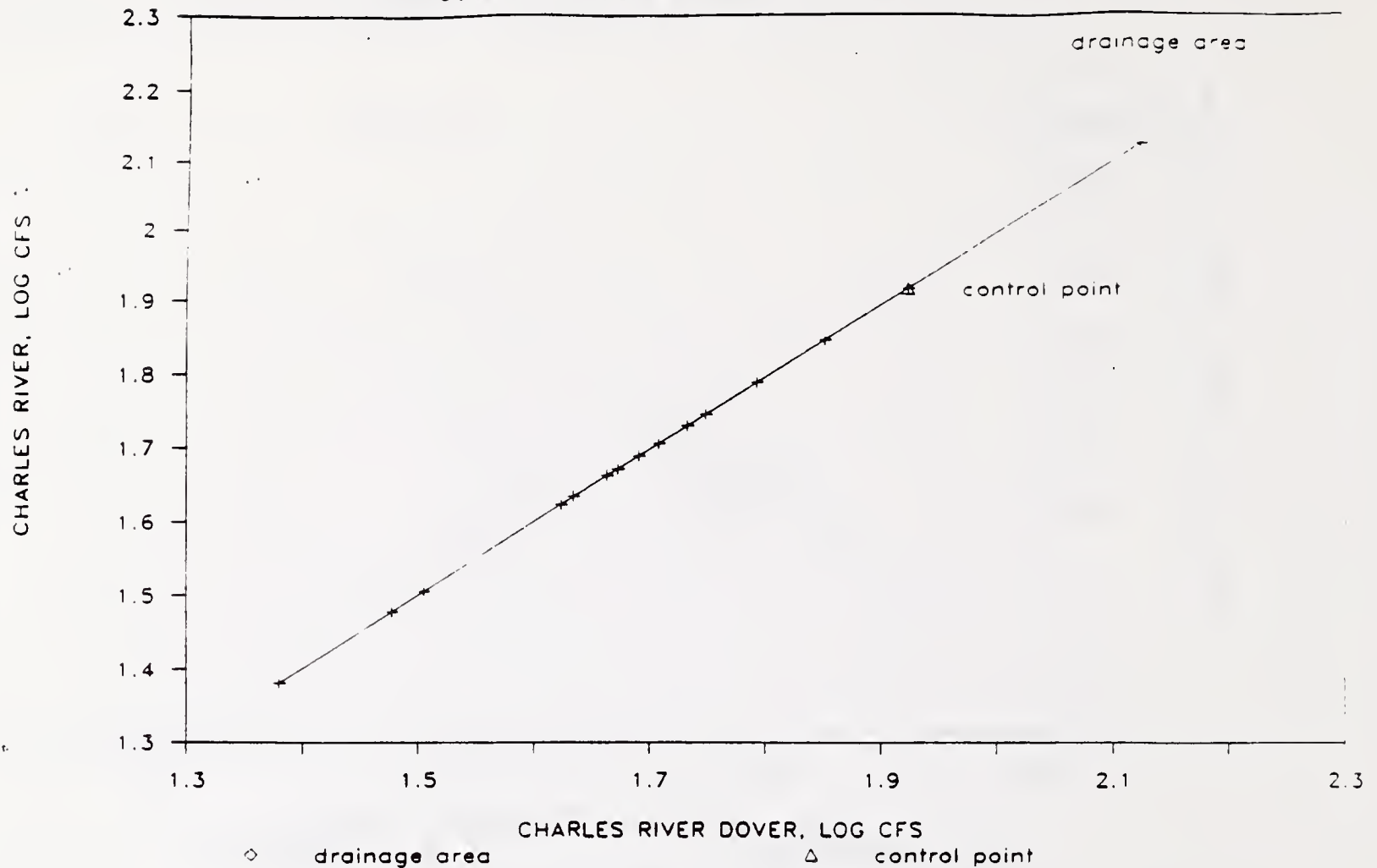
FULLER, WABAN, BOGLE				CHARLES RIVER AT DOVER						
Subbasin				Index Station						
-----				-----						
LOG :				LOG :						
ADJUSTED DISCHARGE DISCHARGE :				ADJUSTED DISCHARGE DISCHARGE :				RESULT OF		
DATE OF	DISCHARGE PER SQR	PER SQR	:	DISCHARGE PER SQR	PER SQR	:	REGRESSION ANALYSIS			
MEASUREMENT	(CFS)	MILE	MILE :	(CFS)	MILE	MILE :				
-----				-----				-----		
08-30-68*(1)	0.65	0.165	-0.781 :	35	0.190	-0.721 :				
09-24-68*(1)	0.20	0.051	-1.293 :	40	0.217	-0.663 :	R Squared	0.406		
10-15-68*(1)	0.32	0.081	-1.089 :	45	0.245	-0.612 :				
07-07-69 (1)	0.46	0.117	-0.932 :	59	0.321	-0.494 :	Regression			
08-25-69*(1)	0.48	0.122	-0.913 :	49	0.266	-0.575 :	Line Equation:			
07-27-70 (1)	0.44	0.112	-0.951 :	59	0.321	-0.494 :	Y = 1.705(X) + 0.149			
07-31-70 (1)	0.47	0.120	-0.922 :	50	0.272	-0.566 :				
08-10-70 (1)	0.30	0.076	-1.117 :	38	0.207	-0.685 :				
10-09-70 (1)	0.63	0.160	-0.795 :	45	0.245	-0.612 :	Drainage Sand & Gravel			
08-26-83 (3)	0.23	0.051	-1.293 :	54	0.293	-0.532 :	Basin Area (sm) Area (sm)			
08-29-68 (2)	0.16	0.193	-0.715 :	34	0.185	-0.733 :	-----			
09-20-68*(2)	0.10	0.120	-0.919 :	47	0.255	-0.593 :	Fuller/Waban	15.7	9.57	
09-25-68*(2)	0.10	0.120	-0.919 :	40	0.217	-0.663 :				
10-15-68 (2)	0.08	0.096	-1.016 :	45	0.245	-0.612 :	Fuller			
07-07-69 (2)	0.26	0.313	-0.504 :	59	0.321	-0.494 :	Brook (1)	3.9	---	
08-25-69*(2)	0.16	0.193	-0.715 :	49	0.266	-0.575 :				
07-31-70 (2)	0.17	0.205	-0.689 :	50	0.272	-0.566 :	Waban Bk.			
08-10-70 (2)	0.14	0.169	-0.773 :	38	0.207	-0.685 :	Bogle Bk.(2)	0.8	---	
10-12-70 (2)	0.09	0.108	-0.965 :	40	0.217	-0.663 :	Bogle Bk.(3)	4.5	---	
control point	9.57	0.609	-0.216 :	84	0.457	-0.341 :	Charles River			
								at Dover	184.0	84.0

* Double Weighted

Figure 18

CHARLES RIVER/CHARLES RIVER, DOVER

SUBBASIN/INDEX STATION FLOW CORRELATION



CHARLES RIVER, DOVER Subbasin			CHARLES RIVER AT DOVER Index Station		RESULT OF REGRESSION ANALYSIS
DATE OF MEASUREMENT	ADJUSTED DISCHARGE (CFS)	LOG ADJUSTED DISCHARGE	ADJUSTED DISCHARGE (CFS)	LOG ADJUSTED DISCHARGE	
08-30-68	24	1.380	24	1.380	R Squared 1 Regression Line Equation: Y = X
10-01-68	30	1.477	30	1.477	
10-18-68	32	1.505	32	1.505	
07-11-69	43	1.633	43	1.633	
09-25-69	62	1.792	62	1.792	
07-28-70	47	1.672	47	1.672	
09-10-82	62	1.792	62	1.792	
09-13-82	54	1.732	54	1.732	
09-20-82	42	1.623	42	1.623	
07-20-83	46	1.663	46	1.663	
07-29-70	56	1.748	56	1.748	Drainage Sand and Gravel Basin Area (sm) Area (sm) Charles River at Dover 184.0 84.0 Charles River Dover Subbasin 26.4 12.5
10-31-69	71	1.851	71	1.851	
08-26-83	51	1.708	51	1.708	
06-24-83	134	2.127	134	2.127	
07-20-83	49	1.690	49	1.690	
control point	84	1.924	84	1.924	

From the above factors, the location of the regression line (curve of relation) can be fixed by the refined discharge measurements, while the slope of the line is defined by the stratified drift ratio.

The curve of relationship for each of the subbasins is examined under the index station method. A regression analysis is performed on the data points as described above and the logs of those numbers are plotted. Streamflow measurements were double weighted where appropriate, based on the previously described assessment of data quality. The stratified drift area point referred to as the control point on the graph, was triple weighted. The plot of the drainage areas was not used in the regression analysis and is shown for illustrative purposes only.

In three subbasins (Mill River, Bogastow Brook, and Fuller/Waban Brook), there were not enough usable data points to establish a valid correlation. Therefore, other measuring locations (indicated on the baseflow/index station figures) within the subbasin were incorporated into the data base. The measurements were normalized using the drainage area to yield a discharge per square mile (cfsm) value. The procedure that was used to correlate baseflow in the other subbasins was utilized to correlate these three subbasins. The log of the cfsm value was then plotted against the cfsm log of the index station measurements. The control point and the drainage area plot were also divided by the respective drainage areas and their corresponding log values were used.

5. Yield Derivation

Subbasin yield is an expression of how much water is available for use within a subbasin. In the supply and demand analysis it is the supply side of the equation. For purposes of the Charles River Basin Plan, subbasin yields available 90, 95, 98, and 99 percent of the time during the planning drought of the early 1980's and for the period of record were examined. A range of reliability is presented; however, the strict standard used for the river basin planning program uses the flow available 99 percent of the time and is considered the yield of the subbasin. The subbasin yields using the period of record flow durations are calculated for comparison.

To determine the yield available during the planning drought, the flow duration of concern (99%) must be determined for the index station. To obtain the 99 percent flow for each subbasin; the flow available 99 percent of the time as shown on the graph is inserted into the line equation developed for each subbasin. This procedure can be used to estimate yield values for any low flow flow duration as long as the input data remains below the confines of the greatest data point.

For all subbasins examined by the Index Station Method, the regression line equation on each figure represents the relationship between the discharges of the index station and the

subbasin shown. Since the correlation is based on low flow measurements, this relationship is valid only for low flows and should not be extrapolated above the largest value plotted. Table 4 indicates the virgin yields available for various flow durations for the 11 subbasins for both the early 1980's drought and the period of record. For the 99 percent flow duration, during the 1980's drought, the yields range in size from 0.1 cfs in Chicken Brook to 3.1 cfs in the Charles River, Medfield subbasin. Virgin yield available for the three main stem subbasins were obtained by subtracting the yields for the subbasins which are tributaries to the mainstem subbasin from the overall yield of the larger mainstem subbasin. This procedure was followed for the Charles River, Millis gage, the Charles River Medfield gage and the Charles River, Dover gage subbasins (Table 5).

B. Aquifer Yield Method

The Aquifer Yield Method was employed in those subbasins which are located downstream of the Dover Gage Index Station. This section of the basin is comprised of the Charles Wellesley, Rosemary Brook, Charles Waltham, Stony Brook and the Charles 128 subbasins. These subbasins, which are heavily influenced by human activities, lend themselves more readily to the Aquifer Yield Method than the Index Station Method. The aquifer areas in this section of the basin also coincide closely with the subbasins of the study area. In the upstream reaches of the basin, stratified drift aquifers transcend subbasin boundaries making them unusable for subbasin yield calculation by the aquifer yield method.

1. US Geological Survey Aquifer Yield Prediction Methodology (Chapter 800 Charles River Basin Study)

The subbasin yields estimated using the aquifer yield methodology originate from aquifer yields developed by the U.S. Geological Survey (Myette, Simcox, 1989). Yields of the aquifers in the subbasins were quantified by evaluating the amount of water available through ground water recharge/discharge.

Recharge to aquifers is mostly derived from precipitation which will cause an aquifer to continuously discharge ground water to streams, ponds, lakes, and wetlands. In a year of average precipitation, aquifers are recharged starting after the usual lows in October and November to maximum overflow conditions in the late spring. As evapotranspiration reduces runoff in late spring, ground water contribution to streamflow becomes more of a factor through summer and a maximum factor during usual low flow period of August and September. This ground water discharge comprises most of the flow in streams during low flow periods. During periods of average precipitation, aquifer discharge equals aquifer recharge and ground water in storage remains about the same from year to year.

Table 4
ESTIMATED VIRGIN YIELDS
OF SUBBASINS UPSTREAM OF
THE CHARLES RIVER AT DOVER GAGE

Subbasin	1980-1981 Drought				Recent Period of Record (1960-1987)			
	90 % CFS	95 % CFS	98 % CFS	99 % CFS	90 % CFS	95 % CFS	98 % CFS	99 % CFS
Charles River Dover Index Station	39.0	28.3	19.5	18.1	43.4	31.6	22.5	18.8
Upper Charles	2.3	1.7	1.3	1.2	2.5	1.9	1.4	1.2
Hopping Brook	0.7	0.5	0.3	0.2	0.8	0.5	0.3	0.3
Mine Brook	3.8	3.2	2.7	2.6	4.1	3.4	2.9	2.6
Chicken Brook	0.4	0.2	0.1	0.1	0.5	0.3	0.1	0.1
Mill River	4.5	3.2	2.2	2.0	5.0	3.6	2.5	2.1
Charles River Millis	6.5	4.6	2.8	2.6	7.2	5.2	3.5	2.7
Stop River	3.6	2.8	2.0	1.9	3.9	3.0	2.3	2.0
Bogastow Brook	1.4	1.4	1.3	1.3	1.5	1.4	1.3	1.3
Charles River Medfield	8.0	5.4	3.4	3.1	9.1	6.3	4.2	3.3
Fuller & Waban Brook	1.4	0.8	0.4	0.4	1.7	1.0	0.5	0.4
Charles River Dover	6.4	4.5	3.0	2.7	7.1	5.0	3.5	2.8

Estimated Virgin Yields of Charles River Main
Stem Subbasins Upstream of the Dover Gage

Table 5

CHARLES RIVER, MILLIS SUBBASIN
ESTIMATED VIRGIN YIELD

Subbasin	1980-1981 Drought				Recent Period of Record (1960-1987)			
	90 % CFS	95 % CFS	98 % CFS	99 % CFS	90 % CFS	95 % CFS	98 % CFS	99 % CFS
Charles River Millis Gage	18.2	13.4	9.4	8.7	20.1	14.9	10.7	9.0
Mill River	4.5	3.2	2.2	2.0	5.0	3.6	2.5	2.1
Upper Charles	2.3	1.7	1.3	1.2	2.5	1.9	1.4	1.2
Hopping Brook	0.7	0.5	0.3	0.2	0.8	0.5	0.3	0.3
Mine Brook	3.8	3.2	2.7	2.6	4.1	3.4	2.9	2.6
Chicken Brook	0.4	0.2	0.1	0.1	0.5	0.3	0.1	0.1
Charles River Millis Subbasin	6.5	4.6	2.8	2.6	7.2	5.2	3.5	2.7

CHARLES RIVER, MEDFIELD SUBBASIN
ESTIMATED VIRGIN YIELD

Subbasin	1980-1981 Drought				Recent Period of Record (1960-1987)			
	90 % CFS	95 % CFS	98 % CFS	99 % CFS	90 % CFS	95 % CFS	98 % CFS	99 % CFS
Charles River Medfield Gage	31.2	23.0	16.1	15.0	34.6	25.6	18.5	15.6
Stop River	3.6	2.8	2.0	1.9	3.9	3.0	2.3	2.0
Bogastow Brook	1.4	1.4	1.3	1.3	1.5	1.4	1.3	1.3
Charles River Millis Gage	18.2	13.4	9.4	8.7	20.1	14.9	10.7	9.0
Charles River Medfield Subbasin	8.0	5.4	3.4	3.1	9.1	6.3	4.2	3.3

CHARLES RIVER, DOVER SUBBASIN
ESTIMATED VIRGIN YIELD

Subbasin	1980-1981 Drought				Recent Period of Record (1960-1987)			
	90 % CFS	95 % CFS	98 % CFS	99 % CFS	90 % CFS	95 % CFS	98 % CFS	99 % CFS
Charles River Dover Gage	39.0	28.3	19.5	18.1	43.4	31.6	22.5	18.8
Charles River Medfield Gage	31.2	23.0	16.1	15.0	34.6	25.6	18.5	15.6
Fuller & Waban Brook	1.4	0.8	0.4	0.4	1.7	1.0	0.5	0.4
Charles River Dover Subbasin	6.4	4.5	3.0	2.7	7.1	5.0	3.5	2.8

To estimate the potential aquifer yields available from intercepted ground water discharge for stratified drift aquifers in the Charles River basin, flow duration curves were developed for the largest stream draining each aquifer using a method developed by Thomas (1966). Thomas produced a family of flow-duration curves by relating the geology of a drainage area to the low flows at several continuous-record streamflow gaging stations in Connecticut. The curves are for unregulated streams that have a mean annual flow of 1.16 mgd/mi² (millions of gallons per day per square mile), and are based on the period from October 1930 to September 1960. The lower part of these curves (flows equaled or exceeded 80 to 99.9 percent of the time) show that low flows are related to the percentage of drainage area underlain by coarse-grained stratified drift and by till-mantled bedrock. Studies summarized by Cervione and others (1982) indicate that the average annual ground water discharge is about three times greater in areas underlain by coarse-grained stratified drift than in areas underlain by till and bedrock.

2. Subbasin Yields (below Dover gage)

For the Charles River basin, a map of ground water favorability (Walker and others, 1975) was used by U.S.G.S. to determine the percentage of each basin covered by stratified drift. Streamflows at the 95 and 99 percent flow durations on the flow duration curves developed for streams in the basin provided estimates of potential yield from intercepted ground water discharge, unadjusted for current withdrawals.

The aquifer and the surrounding till area which provides it with ground water, produce the long term yields for the aquifers as estimated by U.S.G.S. However, the subbasins delineated for the basin plan may comprise an area larger than the aquifer and the immediately adjacent drainage area. Where this situation exists, a value of 0.1 cubic feet per second per square mile (cfs/m) was used to represent the yield component of till to the subbasin (Walker and others, 1975). The 0.1 cfs/m was used only for the till area not included in the drainage area of the aquifer and is valid specifically for periods of low flow. Table 6 presents the virgin yields for these five downstream subbasins as calculated by the Division of Water Resources. The yields are estimated for the 95% and 99% flow duration. The basis for these estimations, the USGS aquifer yields, was calculated only for the flows available 95 and 99 percent of the time for the period of record.

DWR obtained the yields available in the five lower Charles River subbasins for the early 1980's drought by using the Charles River Dover index station. For the flow durations used, the relationship between the adjusted discharges at the index station for the recent period of record (1960-1987) and the early 1980s drought was calculated. Based on this comparison, the early-1980's drought yields were estimated for the 5 subbasins.

Table 6

ESTIMATED VIRGIN SUBBASIN YIELDS
DOWNSTREAM OF THE CHARLES RIVER DOVER SUBBASIN

	Charles River Rt. 128 Subbasin	Charles River Wellesley Subbasin	Rosemary Brook Subbasin	Stony Brook Subbasin	Charles River Waltham Subbasin
Subbasin Drainage Area (sq. mi.)	9.0	19.2	3.9	24.0	12.0
Aquifer Area (sq. mi.)	2.7	19.2	3.9	15.0	12.0
Stratified Drift Area (sq. mi.)	0.3	7.5	2.2	5.4	2.4
Aquifer Yield * Recharge (cfs) **					
95 %	0.2	7.8	2.5	3.7	2.3
99%	0.1	5.4	2.0	2.3	1.2
Subbasin Yield Recharge (cfs) ** 1960-1987 Period of Record					
95 %	0.8	7.8	2.5	5.1	2.3
99%	0.7	5.4	2.0	3.7	1.2
Subbasin Yield Recharge (cfs) ** 1980-1981 Drought					
95 %	0.7	7.0	2.2	4.5	2.0
99%	0.7	5.2	1.9	3.6	1.1

notes:

* From U.S. Geological Survey, Water Resources of the Charles River Basin,
WRI 88-4173.

** Yield from recharge component only.

The 1980's drought yields range from a low of 0.7 cfs in the Charles River Rt. 128 subbasin at the 99 percent flow duration to a high of 5.2 cfs at the Charles River Wellesley subbasin. Yields at the 99 percent flow duration for the 1980's drought are at about the 96 percent flow duration for the 1960 through 1987 period at the Dover streamflow gage.

C. Subbasin Inflows and Outflows

In order to properly evaluate streamflow characteristics, the amount of water withdrawn from and discharged into each subbasin must be considered. Monthly pump data for each public water supply source was obtained from the 1988 statistics form submitted by each public water supplier to the DEP, Division of Water Supply. Wastewater discharges into each subbasin were estimated by determining the areas of each community served by public sewer and those where private septic systems are utilized. A 10 percent loss factor was used for septic system discharges during the summer when there are evaporative conditions. Water from public supplies often is transferred between subbasins or across the river basin boundary, and may be discharged in several locations.

The proportions of town populations residing in each subbasin were estimated by examining the population centers shown on topographic maps and through discussions with town officials. This subbasin analysis calculates how much water each subbasin gains or loses due to transfers between subbasins. From these subbasin calculations, the changes in Charles River or tributary streamflow at each low flow measuring point was determined.

Upper Charles Subbasin #1

This subbasin, covering 80 percent of Milford and about 10 percent of Bellingham, lost an average of 0.09 mgd during the summer of 1988. While all of Milford's total demand of 4.02 mgd came from sources in the subbasin, all of Bellingham's total demand of 1.70 mgd was obtained outside the subbasin. The Milford Water Company sold 0.12 mgd to Hopedale and Mendon in the Blackstone River basin. About 0.06 mgd was lost to evaporation by the 15 percent of Milford water users who have septic systems. About 0.08 mgd was transferred to subbasin #6, where about two percent of Milford's users live. Bellingham residents in the subbasin imported about 0.17 mgd from subbasin #6 and the Taunton River basin and then discharged it into their septic systems. In sum, the subbasin had a net loss of 0.09 mgd during the summer of 1988.

Hopping Brook Subbasin #2

The Hopping Brook Subbasin includes about 10 percent of Holliston's population, two percent of Milford's population and a few Medway residents. Holliston well #4 pumped 0.29 mgd during the summer of 1988 and about 0.18 mgd was discharged by Holliston septic systems in the subbasin. The 0.08 mgd transfer from subbasin #1 added 0.08 mgd for Milford residents. Overall, there was no net water withdrawal or transfer from this subbasin.

Mine Brook Subbasin #3

The Mine Brook subbasin covers about two-thirds of Franklin where approximately 70 percent of the town's people reside. Franklin wells #1, #2, #3, #6, and #7 pumped 1.39 mgd during the summer of 1988. With about two-thirds of the subbasin served by public sewer, 1.24 mgd was transferred by sewer from this subbasin to the Medway regional treatment plant in the Charles River Millis subbasin #6. The subbasin gained about 0.60 mgd from the septic wastewater discharge of the one-third unserved residences. Overall, there was a net loss of about 0.64 mgd from the subbasin.

Chicken Brook Subbasin #4

The Chicken Brook subbasin covers about 50 percent of Medway and 15 percent of Holliston. There are no active public water supply sources in the subbasin. With 52 percent of Medway and 100 percent of Holliston using septic systems for wastewater discharge, about 0.23 mgd and 0.27 mgd were contributed to the subbasin respectively. Overall, about 0.50 mgd was added to the subbasin during the summer of 1988.

Mill River Subbasin #5

The Mill River subbasin includes about 60 percent of Wrentham's population and 20 percent of Franklin's population. While Wrentham wells #2 and #3 pumped 0.87 mgd during the summer of 1988, about 0.72 mgd was discharged into the subbasin by Wrentham residents through septic systems. There is no public sewer system in Wrentham. Franklin wells #4, #5, and #8 pumped about 1.15 mgd while the 40 percent unsewered Franklin population in the subbasin discharged about 0.20 mgd through septic systems. Overall, there was a net loss of 1.13 mgd from this subbasin.

Charles River-Millis Subbasin #6

The Charles River-Millis subbasin covers portions of Norfolk, Franklin, Bellingham, Milford, Medway, and Millis along the main stem of the Charles River. Overall there was a net gain of 0.86 mgd to this subbasin during the summer of 1988. Approximately 2.24 mgd was discharged to the Medway regional treatment plant in the subbasin from Medway, Franklin and Millis. About 0.93 was added to the subbasin through septic systems. The subbasin includes the following approximate percentages of each town's populations: about 10 percent of unsewered Norfolk; 10 percent of Franklin (50% sewerd); 35 percent of unsewered Bellingham; 40 percent of Medway (48% sewerd); and two percent of Milford. During the 1988 summer 2.31 mgd was pumped from subbasin #6 wells in the three towns: the Gold St. Well in Norfolk (0.41 mgd); Bellingham wells #5 and #8 (0.78 mgd); and Medway wells #1 and #3 (1.12 mgd).

Stop River Subbasin #7

The Stop River subbasin covers very small portions of Wrentham, Walpole and Medfield, and two-thirds of Norfolk where about 75 percent of the town's population lives. About 0.28 mgd is transferred from the Gold St. well in the Charles

River-Millis subbasin #6 and discharged through septic systems in this subbasin during the summer of 1988. The MCI-Norfolk facility, which has a wellfield along the Stop River, used about 0.54 mgd and discharged that water back into the river. Overall, about 0.28 mgd was added to this subbasin.

Bogastow Brook Subbasin #8

The Bogastow Brook Subbasin includes 75 percent of the population of the town of Holliston, 35 percent of Millis and 10 percent of Medway. Holliston wells #1, #2, #5 and #6, which together pumped 1.47 mgd during the summer of 1988 are the only withdrawals in the subbasin. Residents in unsewered Holliston discharged about 1.19 mgd in the subbasin. One-third of Millis residents in the subbasin utilized septic systems to discharge about 0.19 mgd. One-half of Medway residents in the subbasin discharge about 0.06 mgd through septic systems. Overall, there is no net withdrawal or addition of water from this subbasin.

Charles River-Medfield Subbasin #9

The Charles River-Medfield subbasin covers about 90 percent of Medfield and 65 percent of Millis. Medfield wells #1 and #2 pumped 0.43 mgd during the summer of 1988 while the same amount of water was sent to Medfield's sewage treatment plant in the subbasin. The 65 percent of Medfield residents utilizing septic systems discharged about 0.64 mgd into the subbasin. Millis wells #3 and #4 withdrew 0.84 mgd from the subbasin while 0.31 mgd was discharged into the subbasin by Millis residents through septic systems. Overall, there was a net gain of 0.11 mgd to the subbasin.

Fuller Brook Subbasin #10

The Fuller Brook subbasin covers over half of Wellesley, 20 percent of Weston, and portions of Natick, Needham and Wayland. In Wellesley, the town's Morse's Pond well pumped 1.15 mgd and Wellesley College's well pumped 0.45 mgd with all of that water transferred out of basin through the MWRA's regional sewer system. Natick's Pine Oaks and Morse's Pond wells pumped 0.05 mgd from the subbasin and was transferred out of basin by the MWRA sewer system. The 25 percent of Weston's residents who live in the subbasin (and use MWRA water) discharged about 0.47 mgd into septic systems. Overall, there was a net loss of 1.18 mgd from the subbasin during the summer of 1988.

Charles River-Dover and Natick Subbasin #11

This subbasin covers large portions of Sherborn and Dover and a small portion of Needham. Needham wells #1, #2, and #3 pumped 3.53 mgd during the summer of 1988 and all of that water was transferred out-of-basin through the MWRA sewer systems and do not transfer water out of the subbasin. Dover has several small public water supply systems that serve homes which have on-site septic systems. No significant amount of water is transferred in or out of basin in Dover. Overall, there was a net loss of 3.53 mgd from the subbasin.

Charles River-Rte. 128 Subbasin #12

The Charles River-Rte. 128 subbasins covers portions of Needham, Dedham and Westwood. The Dedham-Westwood Water District's Rock Meadow well pumped 0.43 mgd during the summer of 1988. Since all portions of these three communities are sewered out to the MWRA system, there was a net loss of 0.43 mgd from this subbasin.

Charles River-Wellesley Subbasin #13

This subbasin covers portions of Westwood, Dedham, Needham, Boston, Brookline, and Newton. The Dedham-Westwood Water District's Bridge Street wellfield, which pumped 1.07 mgd during the summer of 1988, is the only active water supply source in the subbasin. Since all of the communities in the subbasin are sewered to the MWRA, there was a net loss of 1.07 mgd from the subbasin.

Rosemary Brook-Subbasin #14

The Rosemary Brook subbasin covers portions of Wellesley and Needham. Wellesley's wells in the subbasin, named Wellesley Ave., Rosemary, Longfellow, and T.F. Coughlin, pumped 1.25 mgd during the summer of 1988. Since both communities are sewered to the MWRA, there was a net loss of 1.25 mgd from the subbasin.

Stony Brook Subbasin #15

The Stony Brook subbasin covers portions of Weston, Waltham, Lincoln and Lexington. Cambridge's Hobbs Brook and Stony Brook Reservoirs in the subbasin provided the city with 17.75 mgd during the summer of 1988. All of that water was transferred out of the subbasin to Cambridge. Lincoln's Sandy Pond Reservoir and Tower Road well pumped about 0.34 mgd and about 0.11 mgd was transferred to Lincoln residents in the Concord River basin. Overall, there was a net loss of about 17.86 mgd from the subbasin.

Charles River-Waltham Subbasin #16

This subbasin covers portions of Newton, Wellesley, Weston and Waltham. There are no active public water supply sources in this subbasin. Approximately 20 percent of Weston's residents live in this subbasin and discharge about 0.41 mgd through septic systems. Overall, there was a net gain to the subbasin of 0.41 mgd.

D. Existing Subbasin Yields

The subbasin yields available for the planning drought under unregulated conditions and after the public water uses have been accounted for (as shown in the previous section) are presented in Table 7. The unregulated (virgin) flow has been determined by removing reported consumption. From Table 7 one can determine how much yield is available for future withdrawals during the planning drought, prior to consideration of a minimum streamflow threshold.

Table 7
ESTIMATED SUBBASIN YIELDS
CHARLES RIVER BASIN - EARLY 1980'S DROUGHT

SUBBASIN NAME	VIRGIN YIELD (CFS)		ADJUSTMENTS * FOR CURRENT USE (CFS)	ADDITIONAL POTENTIAL YIELD (CFS)	
	FLOW DURATION			FLOW DURATION	
	99 %	95 %		99 %	95 %
Upper Charles	1.2	1.7	-0.1	1.1	1.6
Hopping Brook	0.2	0.5	0.0	0.2	0.5
Mine Brook	2.6	3.2	-1.1	1.5	2.1
Chicken Brook	0.1	0.2	0.8	0.9	1.0
Mill River	2.0	3.2	-1.7	0.3	1.5
Charles River, Millis	2.6	4.6	1.3	3.9	5.9
Stop River	1.9	2.8	0.4	2.3	3.2
Bogastow Brook	1.3	1.4	0.0	1.3	1.4
Charles River, Medfield	3.1	5.4	0.2	3.3	5.6
Fuller/Waban Brook	0.4	0.8	-1.8	-1.4	-1.0 **
Charles River, Dover	2.7	4.5	-5.5	-2.8	-1.0 **
Charles River, 128	0.7	0.7	-0.7	0.0	0.0
Charles River, Wellesley	5.2	7.0	-1.7	3.5	5.3
Rosemary Brook	1.9	2.2	-1.9	0.0	0.3
Stony Brook	3.6	4.5	-27.3	-23.7	-22.8 **
Charles River, Waltham	1.1	2.0	0.0	1.1	2.0

* Minus indicates a loss from the subbasin,
and plus indicates a gain into the subbasin.

** Existing demand is met through storage:
either through induced infiltration or
surface water reservoirs.

Several subbasins appear to have adequate yield available while other subbasins appear significantly over stressed. For example, the Fuller/Waban Brook, the Charles River-Dover and the Stony Brook subbasins use more water on a day-to-day basis than is available in the subbasins during the simulated early 1980's drought.

In these subbasins, as well as in other examined subbasins, current demand is met either through induced infiltration from the Charles River, by adjacent wells, or through surface water storage, as is the case of Stony Brook subbasin (Cambridge Reservoirs). For example, the USGS (Myette and Simcox 1989) estimated the aquifer in the Fuller/Waban Brook and Charles River, Dover subbasins to yield 19 cfs 95 percent of the time and 8.7 cfs 99 percent of the time from induced infiltration; however, both yields are calculated irrespective of a minimum streamflow threshold.

Pumping large amounts of ground water causes streamflow to decline, therefore theoretical yields need to be adjusted to maintain specified minimum streamflows. Aquifer yields from induced infiltration are also provided by the U.S.G.S. for the Medway aquifer (12 cfs at 95 percent flow duration, 8.7 cfs at 99 percent flow duration), Cutler Park Aquifer (20 cfs at the 95 percent flow duration, 8 cfs at the 99 percent flow duration) and the Newton/Waltham aquifer (23 cfs at the 95 percent flow duration, 4.5 cfs at the 99 percent flow duration).

The yield available at Rosemary Brook subbasin is approximately equal to the net demand on the subbasin, while all other subbasins have some additional yield available for both the 95 percent and 99 percent flow duration.

III. HYDROLOGIC ACCOUNTING MODEL OF THE CHARLES RIVER

A. Methodology

The hydrologic model of Charles River basin includes parameters describing the physical characteristics of the water supply systems and the wastewater disposal systems used in the river basin. Physical components of the basin hydrology such as tributaries, reservoirs, points of diversion, wells, gaging stations and communities have been coded in a spatial context, allowing the computer to interpret geographic locations. Three main physical characteristics of the Charles River basin have been simulated: the mainstem, because no major tributaries enter the Charles River; a localized aquifer, because most of the ground water is in isolated aquifers with close hydraulic connection to the stream (the model does not simulate the entire aquifer but simulates the response of streamflow to pumping wells); and off-channel reservoirs (in the case of Cambridge).

The Charles River basin is divided into smaller subbasins, each identified by a point on the river which is referred to as a node. These subdivisions were made so that no physical component of the same type would lie within the same subbasin. However, a subbasin may contain all the different types of physical objects. For example; a town, a reservoir, a wastewater treatment plant and a tributary may lie within the same subbasin. The exception to this is that any number of wells which affect the same tributary may be within the same subbasin. Wells, reservoirs, or towns that are outside the drainage basin of the river but still affect the basin in some way are coded within subbasins and defined to have zero river drainage area. All subbasin nodes have been numbered in downstream order.

The model simulates the continuous interactions of the river's flow and withdrawals by cycling through discrete "passes" (a pass being a specific function executed on a subset of nodes in downstream order) on a monthly time interval. Monthly flows for the Millis gage, Dover gage, Wellesley gage and Waltham gage are the hydrologic input for the model. The first pass distributes the incremental runoff of the gaging station to each subbasin. When there is a reservoir within a subbasin, the monthly inflow is computed from the product of the drainage area of that reservoir and the average runoff per square mile of the stream gage.

The second pass accounts for streamflow depletion resulting from ground water withdrawals. Streamflow depletion, computed by a method described by Jenkins (1970), is based on well pumpage, distance from the well to the stream, transmissivity, and specific yield. The cumulative effect on streamflow is obtained by summing the effects of each month's pumpage. Whether this depletion of streamflow is interpreted as interception of ground water that would have become streamflow or as infiltration of existing streamflow is not important to

the model. Characteristically, the aquifers are recharged every spring and reach their maximum yearly storage during spring floods. To simulate the spring recharge, the accumulated effects on streamflow for each well are reduced to zero, and an equal amount of surface runoff is prevented from becoming streamflow.

The third pass attempts to satisfy the demand of each community using of a set of existing supply sources, which may include wells, out of basin sources, streamflow diversions, and surface reservoir withdrawals. The model has each system draw water from its existing supply sources in accordance with the list of priorities until the demand is satisfied or until the sources are depleted or their capacities exceeded. Any unsatisfied demand is carried over to the next pass for further operations. As water is used by each town, a fraction returns to the streamflow according to the value of its sewage function for that month.

The fourth pass diverts streamflow to pumped storage reservoirs. The factors which limit the amount of water diverted for each reservoir are the amount of water needed to fill each reservoir and the constraining factor of pump and pipe size.

A minimum streamflow value may be changed to reflect the requirements of the instream uses such as fisheries, recreation, wetlands, wildlife and agriculture. The minimum streamflow used is crucial in the Charles River model in that it is a significant limiting factor for off-stream uses such as reservoirs. The volume of water in off-stream reservoirs, in turn, have a significant role in determining the adequacy of a community system in meeting demand. Raising or lowering the minimum streamflow value will have a significant impact in determining which communities will succeed or fail to meet average day demands.

The fifth pass diverts water from one reservoir to another not directly drawn on by the treatment plant. Three factors limit the amount of water diverted from one reservoir to another: the amount of water needed to fill the receiving reservoir, the constraining factor of pump and pipe size, and the amount of water already in the distributing reservoir.

Extensive data collection was necessary to provide physical and operational parameters for the simulation program. Some of the parameters required for modeling are measurable physical characteristics. These include the drainage area of subbasins and the gaging stations, the usable reservoir storage capacities, and the drainage area and surface area of reservoirs. Codes in the data input indicate whether a reservoir is outside the basin drainage boundary and whether a reservoir receives diverted river water or water transferred from another reservoir. The maximum capacity of pump sizes or pipe sizes between the river and communities, between two

reservoirs, and reservoirs and communities are coded. Wells must be located within their subbasin and the downstream, noncontributing drainage area must be computed. The pumping capacity of each well is recorded and a code indicates which community uses the well. The effects on streamflow caused by well pumpage are computed for each well from the transmissivity and specific yield on the aquifer and distance to the stream. A code indicates the subbasin for each community and each node to be used as an observation node.

A very important parameter in the model is the demand of water. Demand is not constant throughout the year, so an average demand is distributed by a time-demand relationship. The demand for each month is a percent of the average annual demand. The percents are an average of the percents which occurred from 1984 through 1986.

The model considers maximum daily demands of each community system but assumes these demands to be a problem of the town distribution system rather than of the basin. The 1988 average day demand and the projected 1995, 2000, 2010, and 2000 average day demand were used for each community for modeling the proposed supply systems for stage-development analysis (Table 8).

The sewage return function for each community is an estimate of the fraction of the water pumped to the community that returns to streamflow through sewage or septic tank effluent. The percentage is zero for communities in which the sewage is pumped out of the basin. For septic tank effluent, a function was developed that returns most of the used water to streamflow during the winter and spring but reduces the percentage to a low level in summer reflecting both outdoor use of water and increased evapotranspiration. The septic tank function and proper sewerage function are weighted according to the percentage of water users that are sewerage.

The water supply operating rules of a community is another important parameter. These rules are governed by engineering feasibility and water supply system operating tradition and are variable in time; in the model, they are generally held constant. For each community in the model, water is considered to be withdrawn from only one source at a time; thus, each source is coded in order of priority. This priority list is formed to approximate actual operating procedures as closely as possible.

Table 8

Charles River Basin
Base and Projected Average Day Demand

	1986-88	1995	2000	2010	2020
COMMUNITY	BASE ADD (mgd)	PROJECTED ADD (mgd)	PROJECTED ADD (mgd)	PROJECTED ADD (mgd)	PROJECTED ADD (mgd)
BELLINGHAM	1.37	2.06	2.52	3.14	3.38
BOSTON	121.82	124.84	130.90	140.17	149.72
BROOKLINE	8.12	8.71	8.92	9.42	9.89
CAMBRIDGE	16.52	16.92	17.22	17.96	18.74
DEDHAM	2.83	2.96	3.03	3.18	3.32
DOVER	0.11	0.13	0.15	0.20	0.28
FRANKLIN	2.25	3.03	3.37	4.30	4.70
HOLLISTON	1.14	1.32	1.41	1.50	1.60
LINCOLN	0.34	0.36	0.38	0.44	0.49
MEDFIELD	1.05	1.17	1.21	1.30	1.39
MEDWAY	0.77	0.88	0.92	1.02	1.12
MILFORD*	3.35	4.29	5.16	5.45	5.64
MILLIS	0.71	0.78	0.83	0.93	1.04
NATICK	4.72	5.15	5.32	5.66	5.92
NEEDHAM	3.83	4.18	4.28	4.49	4.69
NEWTON	11.42	11.59	11.78	12.30	12.82
NORFOLK	0.31	0.41	0.51	0.66	0.83
SHERBORN					
WALTHAM	9.95	10.40	10.65	11.16	11.66
WATERTOWN	3.88	3.91	3.97	4.14	4.31
WELLESLEY	2.63	2.76	2.83	2.96	3.10
WESTON	1.30	1.45	1.48	1.56	1.68
WESTWOOD	1.32	1.45	1.48	1.55	1.63
WRENTHAM	1.14	1.29	1.36	1.52	1.77
TOTAL:	200.88	210.04	219.69	235.01	249.72

* Base demand does not include sales to Hopedale and Mendon which will continue in the future. 0.40 mgd is added to projected demands for continued sales.

B. Results

The accounting model evaluated each community's existing water supply sources under 1980-1981 drought conditions and 1995, 2000, 2010 and 2020 water supply demands. Most communities were shown to have either average day demand deficits or maximum day demand deficits. An average day demand deficit indicates the community failed to meet its average demand with existing sources. A maximum day demand deficit indicates the community failed to meet peak water demands, usually from high summer usage. Some communities have average day deficits but no maximum day deficits because they have adequate storage in the form of reservoirs, lakes, or an out-of-basin source which can be used for infrequent peak demands, but which do not eliminate a continuing average day shortage.

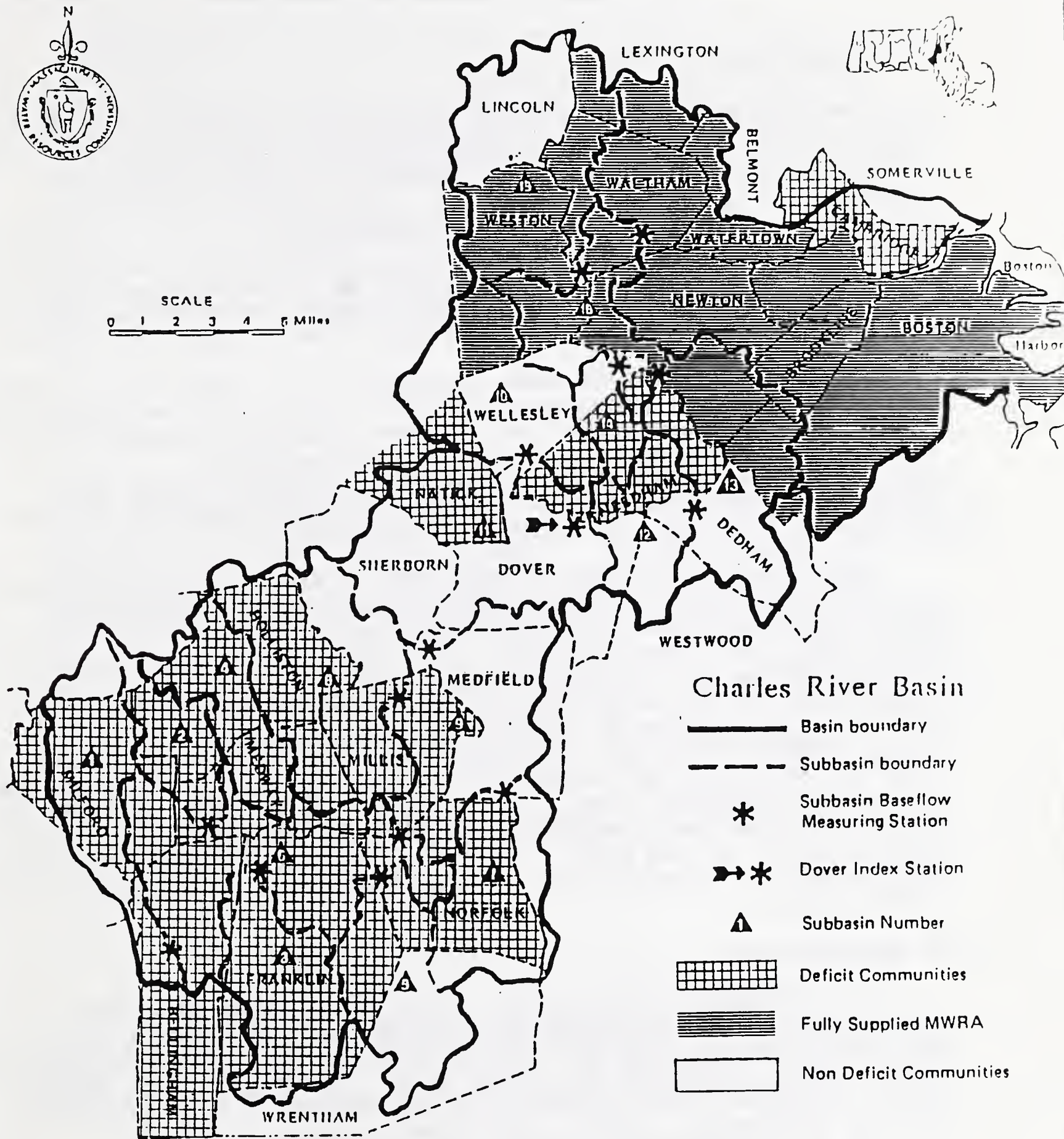
Fifteen water supply systems were modeled (Figure 19). These systems are used by sixteen communities (Dedham and Westwood have a joint water supply system). Boston, Waltham, Watertown, Brookline and Newton are fully supplied by the MWRA, and are not modeled because their water comes from sources entirely out of the Charles River basin. The communities of Dover and Sherborn were not modeled because they receive their water from many small private water companies and on-site wells and return all their water to the basin via on-site septic systems. However, the town of Weston is modeled because it receives all of its water from out of basin and disposes of it in basin, resulting in a net inflow to the basin.

Table 9 summarizes the results of the accounting model and shows the type of deficit for each community and when it would occur under 1980-1981 drought conditions and with 2020 projected demands.

Table 9

Summary of Model Results

Community	Existing Sources	Type of Deficit			
		1995	2000	2010	2020
Bellingham	Cross Street Wells 1,2	ADD	ADD	ADD	ADD
	Wrentham Road Wells 3,4	MDD	MDD	MDD	MDD
	Maple Street Well 8				
	Taunton Street Well 5				
Cambridge	Stoney Brook Reservoir	NONE	ADD	ADD	ADD
	Fresh Pond Reservoir				
	Hobbs Brook (Cambridge) Reservoir				
	MWRA				
Dedham/Westwood	Bridge Street Wellfield	NONE	NONE	NONE	NONE
	Rock Meadow Well				
	White Lodge Wells 1-4				
Franklin	Miller Street Wells 4,5	ADD	ADD	ADD	ADD
	Beaver Pond Wells 1,2	MDD	MDD	MDD	MDD
	Grove Street Wells 3,6				
	Pond Street Well 7				
	Populatic Street Well 8				
Holliston	Brook Street Well 6	MDD	MDD	MDD	MDD
	Central Street Well 5				
	Maple Street Well 2				
	Lake Winthrop Well 1				
	Washington Street Well 4				
Lincoln	Tower Road Well	NONE	NONE	NONE	NONE
	Farrar Pond Well				
	Sandy Pond Reservoir				
Medfield	Route 109 Well 1,2	NONE	NONE	NONE	NONE
	Elm Street Wells 3,4				
Medway	Water Street Well 1	MDD	MDD	MDD	MDD
	Oakland Street Well 2				
	Village Street Well 3				
Milford	Clarks Island Wells	ADD	ADD	ADD	ADD
	Godfrey Brook Wells				
	Dilla Street Wells				
	Charles River				
	Echo Lake				
Millis	Birch Street Well 3	MDD	MDD	MDD	MDD
	South End Pond Well 4				
Natick	Evergreen Well 1,2	NONE	MDD	ADD	ADD
	Springvale Wells 1-5			MDD	MDD
	Morse Pond Well				
Needham	Charles River Street Wells 2,3,5	ADD	ADD	ADD	ADD
	MWRA				
Norfolk	Gold Street Well	NONE	NONE	MDD	MDD
	Tibbets Well				
Wellesley	Morses Pond Wells 1,2	NONE	NONE	NONE	NONE
	Wellesley Ave. Wells 1,2				
	Rosemary Well				
	T.F. Coughlin Well				
	Longfellow Pond Well				
	MWRA				
Wrentham	Lake Pearl Wells 2,3	NONE	NONE	NONE	NONE
	Thurston Street Well				



MODEL RESULTS COMMUNITY WATER SUPPLY STATUS

Notes. Town of Sherborn has no Public Water Supply

Dover Water Supply Agencies were not included in the Model

IV. MINIMUM STREAMFLOW THRESHOLD

A. Introduction

The purpose of establishing a minimum streamflow threshold is to provide a level of protection to the instream uses of the river and to achieve a balance between consumptive and non-consumptive uses of the river. The minimum streamflow threshold is an integral part of the management of the water resources of the basin and can be used as a basis for regulating water withdrawals within the basin and transfers of water out of the basin. This section outlines the estimated streamflow requirements for existing and planned water uses in the Charles River basin and recommends a minimum streamflow for the basin.

The Charles River is used extensively for recreation, water supply, receipt of wastewater effluent, fisheries, wetlands, and wildlife. There are state and private reserves and parks along the river which provide a variety of recreational opportunities. The lower portion of the Charles River is bounded by riverfront parks and boat launches, and trails used for hiking, jogging, bicycling and picnicking.

Of the 24 communities in the Charles River basin study area, only one community, Milford, draws water directly from the Charles River for water supply use. Several communities have wells near the river which may infiltrate water from the river during pumping or intercept water flowing to the river. Seven communities divert water from the basin and 7 communities provide a net inflow of water to the basin by using water from other basins. In 1988, the average daily diversion of water from the basin for all communities was 20.35 million gallons per day (mgd). However, most of this water, 16.09 mgd, is diverted from the Stony Brook Reservoir by the City of Cambridge in the lower portion of the basin. Only 3.81 mgd is diverted from the upper basin. The additional 0.45 mgd leaves the lower portion of the basin.

B. Methodology

The methodology used by the Division of Water Resources to determine a minimum streamflow involves the analysis of historical and statistical streamflow data, geohydrologic data, water supply data, and water use data. The methodology depends on and benefits from the expertise of several state agencies, the U.S. Geological Survey, and other groups.

These agencies provide the locations and streamflow needs of each use in the basin. The available flow at each location is calculated and compared to the estimated flow needs for each water use. The minimum streamflow is iteratively lowered, raised and tested in a digital or analytical model to determine a reasonable threshold which will satisfy most needs, while protecting the environmental quality of the basin.

C. Charles River Streamflow

Estimates of minimum streamflows needed for resident and anadromous fisheries, recreation, wetlands, water supply, agriculture and receipt of wastewater effluent have been collected and analyzed with respect to the flow in the Charles River. Estimated minimum flows range from 0.10 cfs to 0.50 cfs during the low flow months. The percent of time these flows are present or exceeded is listed below:

ESTIMATED MINIMUM FLOW DURATIONS

Flow cfs	Period of Record		80's Drought	
	Annual	June - October	Annual	June - October
0.10	99%	98%	99%	97%
0.50	73%	40%	59%	34%

These percentages are important for balancing the needs of all uses. They indicate that water withdrawals permitted under the Water Management Act may be regulated by the minimum streamflow threshold during a 1-in-20 drought. If that occurs, other means must be found to meet water supply needs. Likewise, the percentages point out the ability of the river to support certain uses and point out periods when uses are more favorable.

Further analysis shows the relation of the monthly flows to these minimums:

MONTHS WHEN FLOW IS BELOW VARIOUS MINIMUMS

Flow cfs	Period of Record	80's Drought
	Months/Year Below	Number of Months/Year Below
0.10	0	0
0.50	2	4

If 0.10 cfs is used as a minimum flow threshold, withdrawals from proposed sources are not, on average, constrained. If 0.50 cfs is used, proposed sources could be regulated (turned off or cut back), on average 2 months every year and 4 months each year of a 1-in-20 year drought.

The 0.10 cfs to 0.50 cfs range of minimum flows was simulated in a computer model to determine the effect of proposed new water withdrawals on the tributaries and mainstem of the river and to determine the magnitude and extent of any community water supply deficits which would occur in the year 2020 under this range of minimum streamflows. The model showed that no deficits occurred with a minimum flow of 0.10 cfs, and all communities with sources in the basin had deficits with a minimum of 0.50 cfs.

Through an iterative process of analyzing potential minimum flows in the model and considering the average monthly flows and the flow durations, the minimum streamflow of 0.21 cfs was found to satisfy the most needs. In addition, a flow of 263 cfs passing Watertown dam is recommended for March, April, and May for migration of smelt. Flow requirements were provided for seven of the eleven instream and out-of-stream uses outlined in the next section. The minimum flow of 0.21 cfs satisfies six of these seven uses, and partially satisfies the seventh use.

D. Inventory of Water Uses

The following inventory includes types of water uses, locations, and estimates of streamflow needs. The information was provided by many state, local, regional, and federal agencies.

WATER USE: Resident Fisheries

SOURCE: Division of Fisheries and Wildlife, Department of Fisheries Wildlife and Environmental Law Enforcement (DFWELE)

RESOURCE: mixed warm water species and cold water fisheries

LOCATIONS: See attached maps (Figures 20-22)

MINIMUM STREAMFLOW:

Main Stem:

- Echo Lake to Milford Center 0.3 cfs
- Milford Center to Medway Dam 0.5 cfs
- Medway Dam to Watertown Dam 0.3 cfs Oct-May
- Watertown Dam to the mouth 0.35 cfs

Tributaries:

- 8 with marginal and seasonal cold water fisheries, 0.5 cfs
- 11 with lowland warm water fisheries, 0.3-0.35 cfs
- 11 with upland and lowland cold water fisheries, no new withdrawals

EXPLANATION: From Cedar Swamp in Milford to the Charles River Dam in Boston mixed warm water species are maintained in the main stem of the Charles River by the Division of Fisheries and Wildlife. Trout are stocked in some reaches in the Spring, but are not maintained year round. The Charles River contains mixed warm water species, sunfish, yellow and white perch, largemouth bass, chain pickerel, white suckers, carp, brown bullheads and goldfish.

Figure 20



Division of Fisheries and Wildlife, DFWELE

 Mixed Warm Water Species

Scale 1:250,000

Charles River Basin



Figure 22



Division of Fisheries and Wildlife, DFWELE

Upland and Lowland Cold Water Fisheries

Scale 1:250,000

Charles River Basin

0 5 10 Miles

WATER USE: Marine Fisheries

SOURCE: Division of Marine Fisheries, DFWELE
Metropolitan District Commission (MDC)

RESOURCE: Anadromous and Catadromous fisheries

LOCATIONS: See attached map (Figure 23)

MINIMUM STREAMFLOW:

Shad:

-- 10-15 cfs July-October

-- 7-10 cfs May-June

Smelt:

-- 263 cfs March-May from the Watertown dam to the
mouth of the Charles River.

EXPLANATION: Anadromous species seasonally present in the Charles River are: American shad, Rainbow smelt, Blueback herring and Alewife. The catadromous species is the American eel. Anadromous fish migrate upstream to spawn from March through May and migrate downstream by October. Smelt migrate up to the Watertown dam. At present, the shad can migrate as far upstream as the Metropolitan Circular Dam in Wellesley/Newton. The MDC is currently constructing fish ladders at the Metropolitan Circular Dam, the Silk Mill Dam, the Cochrane Dam, and the South Natick Dam to allow passage up to Natick. The streamflow requirements listed above are needed for fish passage across the dams. Laundry Brook is a major smelt spawning tributary.

Figure 23



Division of Marine Fisheries

A-B Existing migration routes
B-C Planned migration routes
| Dams

Scale 1:250,000

Charles River Basin

0 5 10 Miles

WATER USE: Receipt of Treated Wastewater Effluent

SOURCE: Division of Water Pollution Control, Department of
Environmental Protection (DEP)

RESOURCE: Wastewater discharge

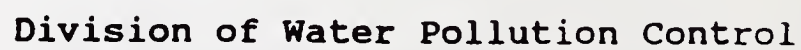
LOCATIONS: see attached map (Figure 24)

MINIMUM STREAMFLOW:

- 0.06 cfs from the headwaters to the Milford WWTP
- 0.08 cfs elsewhere.

EXPLANATION: The Charles River has three classifications over its 80 mile length. From Echo Lake in Milford to Dilla Street in Milford (river mile 78.9 - 76.5) it is Class A, is suitable for water supply. Dilla Street Milford to Watertown Dam is Class B, is suitable for water supply with proper treatment and is also suitable for bathing. Watertown Dam to Charles River Dam is classified as Class C, suitable for recreational boating but is suitable for water supply only under certain conditions and with proper treatment. Table 10 lists the name, type, location, and rating of discharges of wastewater treatment plants in the Charles River basin. The minimum flows are used in the determination of the discharge, such that a minimum dissolved oxygen level of 5-6 ppm is maintained when that low flow is present.

N
↑



Scale 1:250,000

0 5 10 Miles

Table 10

Wastewater Treatment Plants
and
Other Discharges

Name of Discharge	Discharge Type	Location*	Discharge Rating
1. Milford Wastewater Treatment Plant	WWTP effluent	Charles River	Major
2. Charles River Pollution Control District	WWTP effluent	Charles River	Major
3. Medfield Wastewater Treatment Plant	WWTP effluent	Charles River	Major
4. GAF Building Material Corp.	Contact Cooling	tributary to Charles River	Minor
5. Norfolk-Walpole Correctional Inst.	WWTP effluent	tributary to Charles River	Major
6. Pondville State Hospital	WWTP effluent	tributary to Charles River	Minor
7. Wrentham State School	WWTP effluent	tributary to Charles River	Major

* see map for exact location.

Note: Above information from Division of Water Pollution Control, Water Quality of the Charles River, Publication #'s 14292-53-75-1-86-C.R., 1984; 14848-97-50-6-87-CR, 1986.

WATER USE: Municipal Water Supply

SOURCE: Division of Water Resources, DEM;
Division of Water Supply, DEP

RESOURCE: Municipal water supplies in the Charles River Basin

LOCATIONS: See attached map (Figure 25)

MINIMUM STREAMFLOW: 0.10 cfs

EXPLANATION: Only one town, Milford, withdraws water directly from the Charles River. The other 24 communities receive their water from surface water and ground water sources in the basin, or from sources outside the basin. The net diversion of water from the Charles River basin was 20.35 mgd (31.48 cfs) in 1988. Relative to the entire basin drainage area, this diversion is 0.10 cfs. However, most of this water is withdrawn in the lower basin. The amount of water diverted above the Dover gage is 0.03 cfs. The amount of water diverted above the Waltham gage is 0.10 cfs. A minimum streamflow of 0.10 cfs would result in no community deficits due to regulation through the year 2020.

Figure 25



Charles River Basin WATER SUPPLY SOURCES

from
Appendix 3B
Volume I

Water Supply Agency Symbols

- ▲ Ground water supply
- Surface water supply
- P-2 DWR Map symbol

BE	Bellingham Water Department	H	Holliston Water Department
C	Cambridge Water Department	L	Lincoln Water Department
DW	Dedham/Westwood Water District	MF	Medfield Streets, Water & Sewer
Da	Dover Water Company	MW	Medway Water Department
Db	Dover Water Department	ML	Milford Water Company
Dc	Dover Water Works	M	Millis DPW
Dd	Meadowbrook Water Trust	NA	Natick Water Department
De	McNamara Water Works	ND	Needham DPW
Df	Octagon Realty Trust	NO	Norfolk Water Department
Dg	Bedell Water Trust	WE	Wellesley DPW
F	Franklin DPW	W	Wrentham Water Department

Prepared by DEM, Division of Water Resources

WATER USE: Scenic rivers

SOURCE: Rivers Program
Division of Planning and Development, DEM

RESOURCE: Natural, aesthetic and recreational features

LOCATIONS: See attached map (Figure 26)

MINIMUM STREAMFLOW: No specific flow requirements are available.

EXPLANATION: The 38 mile section of the Charles River from Mellen Street in Bellingham to Cochran Dam in Needham has been designated a local scenic river. This designation means that a locally developed management plan has been outlined for this section of the river. The plan, which outlines a protection strategy for the preservation of the natural, aesthetic and recreational features of the river has been approved by the Commissioner of DEM. No specific flow requirements are associated with the management plan or the scenic river designation.

N
↑



WATER USE: Recreation

SOURCE: Charles River Watershed Association
Division of Fisheries and Wildlife, DFWELE, in
cooperation with the Public Access Board

RESOURCE: Adequate river depth and velocity for canoeing,
kayaking, and boating

LOCATIONS: See attached map (Figure 27)

MINIMUM STREAMFLOW:

20 cfs (0.11 cfs) - 160 cfs (0.87 cfs) at Dover
for flatwater canoeing

EXPLANATION: The Charles River is used extensively for canoeing, sailing, kayaking, power boating and rowing. The attached map shows the primary areas for each type of recreation. In general, canoeing and kayaking are predominant in the upper portion of the basin and sailing, rowing and power boating are common in the lower portion of the basin. The minimum flow for canoeing on the Charles River was calculated from minimum and optimum instream flow conditions necessary for recreation, as reported in "Recreation and Instream Flow, Vol. 2," prepared by Jason M. Cortell and Associates and submitted to the Bureau of Recreation (U.S. Dept. of the Interior, 1977).



0 5 10 Miles

WATER USE: Forests and Parks

SOURCE: Division of Forests and Parks, DEM
Division of Planning and Development, DEM
Metropolitan District Commission

RESOURCE: Recreation

LOCATIONS: See attached map (Figure 28)

MINIMUM STREAMFLOW:

Same requirements as canoeing (see Recreation) and
fisheries (see Resident Fisheries).

EXPLANATION: The Department of Environmental Management owns Franklin State Forest, Bristol Blake State Reservation and the Charles River Reservation in the Charles River basin. Of the three properties, only the Charles River Reservation is located on and makes use of the Charles River. Canoeing, birdwatching and fishing are common along the river in the reservation, and could be affected by appreciable changes in streamflow.

In addition to the DEM lands, the Metropolitan District Commission (MDC) owns the roads and parkways along the Charles River from the Needham/Dedham border to the mouth of the Charles River in Boston. Water and related uses facilitated by MDC along the river include fishing, canoeing, boating, sailing and picnicking.

Figure 28



Division of Forests and Parks, DEM

State Forests and Reservations
with water-based recreation

- 1 Franklin State Forest
- 2 Bristol Blake State Reservation
- 3 Charles River Reservation
- 4 MDC Parkways

Charles River Basin

Scale 1:250,000

0 5 10 Miles

WATER USE: Wetlands

SOURCE: Division of Water Resources, DEM
U.S. Army Corps of Engineers
U. S. Soil Conservation Service, University of
Massachusetts at Amherst
Metropolitan Area Planning Council (MAPC)
Massachusetts Department of Public Works

RESOURCE: Wetlands

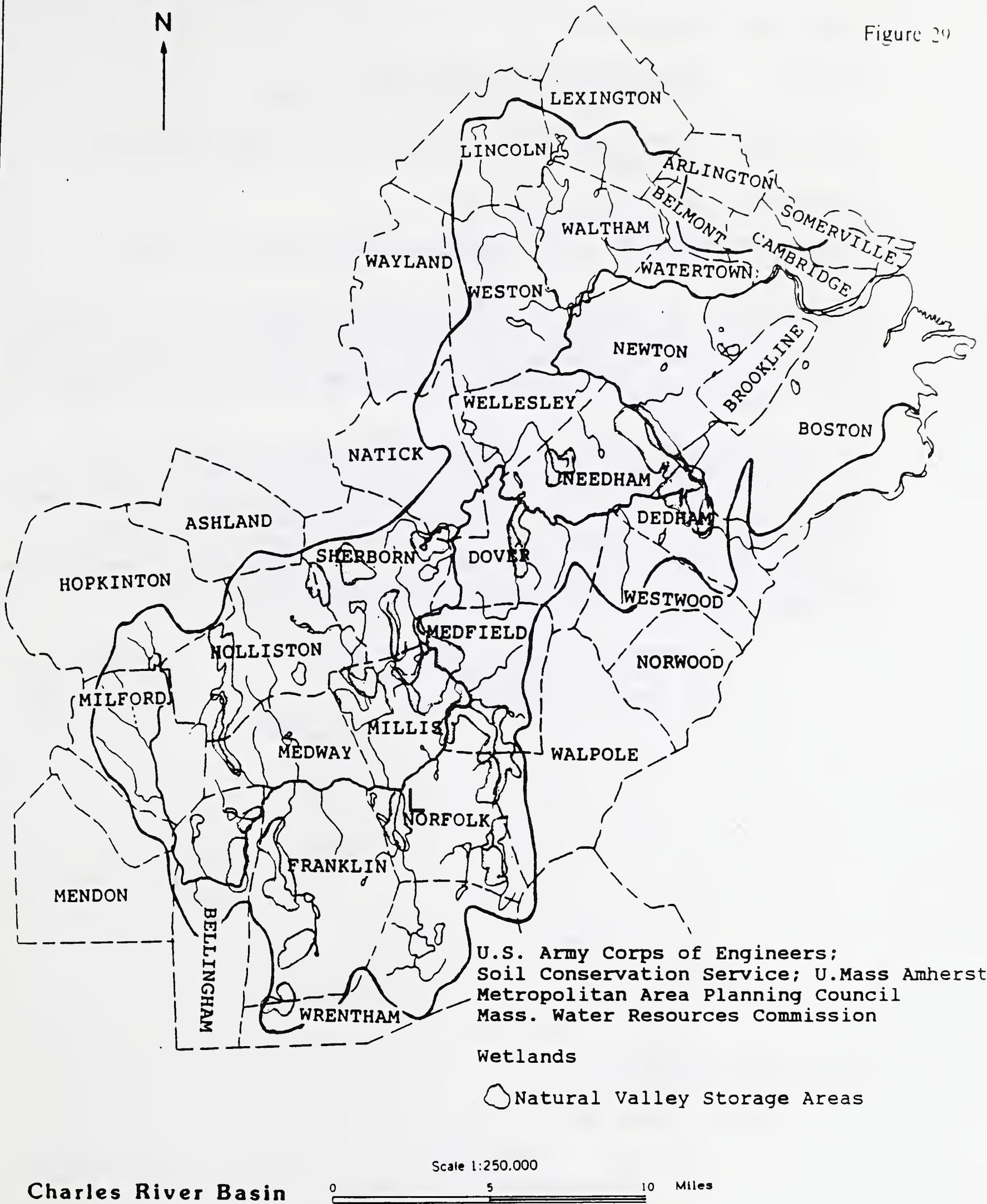
LOCATIONS: see map (Figure 29)

MINIMUM STREAMFLOW: No specific flow requirements are available.

EXPLANATION: Over 22,000 acres of wetlands are present in the Charles River basin. Wetlands are an important resource of the basin because they support wildlife and buffer floods. Wetland vegetative maps show a detailed breakdown of wetland vegetation determined from aerial photographs. The U.S. Army Corps of Engineers mapped areas, called Natural Valley Storage Areas, which are important for controlling floods. Although these areas were not mapped on the basis of wetland vegetation, they are comprised of wetland areas. Approximately 8,100 acres have been protected through fee simple purchase or restrictive easement of flowage as of 1984.

The amount of streamflow needed to maintain the wetland areas is not presently known.

Figure 29



WATER USE: Agriculture

SOURCE: Department of Agriculture
Division of Water Resources, DEM

RESOURCE: Water supply for irrigation of crops and golf
courses.

LOCATIONS: see map (Figure 30)

MINIMUM STREAMFLOW: 0.004 cfs above the Wellesley gage

EXPLANATION: At present the Department of Agriculture is aware of no farming operations which withdraw water directly from the Charles river for irrigation. There are only 12 vegetable farms in the Charles basin, which irrigate from farm ponds and public water supplies.

Two country clubs and one public golf course irrigate their courses with water drawn directly from the Charles River. They are: Leo J. Martin Golf Course, Charles River Country Club, and Dedham Country Club. The estimated 1981-1985 average day withdrawal for irrigation is 0.62 mgd. These withdrawals are usually confined to the period April through October, but may be as short as May through August. The withdrawals with respect to drainage area above the withdrawal points are:

1. Charles River Country Club	0.0015 cfs
2. Leo J. Martin Golf Course	0.0008 cfs
3. Dedham Country Club	<u>0.002 cfs</u>
Total	0.004 cfs

Figure 30



Department of Agriculture;
Division of Water Supply, DEQE

● Golf Courses

Scale 1:250,000

Charles River Basin

0 5 10 Miles

WATER USE: Rare Plant Species

SOURCE: Massachusetts Natural Heritage Program, Division of
Fisheries and Wildlife, DFWELE

RESOURCE: Water for rare flood plain and instream plants

LOCATIONS: see map (Figure 31)

MINIMUM STREAMFLOW: No specific requirements are available.

EXPLANATION: Two rare river-dependent plants are found in the Charles River basin. The Threadfoot lives in the river upstream and downstream of the South Natick Bridge. This plant grows on rocks and stones and depends on an adequate supply of fast flowing water. The River Bulrush is found in floodplains in three towns (see map). This plant depends on spring floods to bring nutrients to the root systems.

Figure 31



E. SUMMARY

The following table summarizes the estimated minimum streamflow requirements for all the water uses in this report. The Division of Marine Fisheries had the highest minimum streamflow requirement for anadromous fish. Uses for which no specific streamflow needs were available, such as wetlands and scenic rivers, are assumed to be served by the marine fisheries flows.

Water Use	Streamflow
Resident Fisheries	
<u>Main Stem:</u>	Echo Lake to Milford Center 0.3 cfsm Milford Center to Medway Dam 0.5 cfsm Medway Dam to Watertown Dam 0.3 cfsm (Oct.-May) * Watertown Dam to the mouth 0.35 cfsm (June-September), same as Marine Fisheries
<u>Tributaries:</u>	-- 8 with marginal and seasonal cold water fisheries, 0.5 cfsm -- 11 with lowland warm water fisheries, 0.3-0.35 cfsm -- 11 with upland and lowland cold water fisheries, no new withdrawals
Marine Fisheries	
<u>Shad:</u>	-- 10-15 cfs** (July-October) -- 7-10 cfs** (May-June)
<u>Smelt:</u>	-- 263 cfs from the Watertown dam to the mouth (March-May).
Wastewater	
	0.06 cfsm headwaters to Milford WWTP 0.08 cfsm elsewhere
Municipal supply 0.10 cfsm	
Scenic Rivers no specific flow requirement available	
Recreation for flatwater canoeing 0.11-0.87 cfsm	
Forest and Parks	
	for canoeing, see Recreation for fishing, see Resident Fisheries
Wetlands no specific flow requirement available	
Agriculture 0.004 cfsm above the Wellesley gage	
Rare plant species	
	no specific flow requirement available

*Where specific flows are not required year round, the applicable dates are given in parentheses.

**These flows are required for passage through MDC fish ladders.

V. References

- Cervione, M.A., Jr, Melvin, R.L., and Cyr, K.A. 1982. A Method for Estimating the 7-day, 10-year Low Flow of Streams in Connecticut: Connecticut Water Resources Bulletin No. 34.
- Commonwealth of Massachusetts, Department of Environmental Protection: Division of Water Supply, One Winter St. Boston; Division of Water Pollution Control, Westboro; Metropolitan Boston Northeast Office, Woborn; Central Office, Worcester;
- Jenkins, C.T. 1970. Computation of Rate and Volume of Stream Depletion by Wells: Techniques of Water Resources Investigations of the U.S. Geological Survey, Water Supply Paper 1826
- Myette, C.F. and Simcox, A.C. 1989. Water Resources and Aquifer Yields in the Charles River Basin, Massachusetts, Water Resources Investigation Report 88-4173, U.S. Department of the Interior, Geological Survey.
- Riggs, H.C. 1972. Low Flow Investigations, Techniques of Water Resources Investigations of the U.S. Geological Survey, U.S. Department of the Interior, Geological Survey.
- Searcy, J.K. 1959. Methods and Practices of the Geological Survey; Manual of Hydrology: Part 2. Low Flow Techniques, Water Supply Paper 1542-A, U.S. Department of the Interior, Geological Survey.
- U.S. Department of the Interior, Geological Survey, Water Data Reports, Massachusetts and Rhode Island, 1937-1986.
- U.S. Geological Survey Geographic Information System. 1989. Surficial Deposits in the Charles Basin, U.S. Department of the Interior, Geological Survey.
- U.S. Geological Survey. 1986. Miscellaneous Measurements, Department of the Interior, Geological Survey, Revised, May.
- Walker, E.H., Wandle Jr., S.W., and Caswell, W.W. 1975. Hydrology and Water Resources of the Charles River Basin, Massachusetts, Hydrologic Investigations Atlas HA-554, U.S. Department of the Interior, Geological Survey.
- Wandle, Jr., W.S. 1984. Gazetteer of Hydrologic Characteristics of Streams in Massachusetts Coastal River Basins of the North Shore and Massachusetts Bay, Water Resources Investigation Report 84-4281, U.S. Department of Interior Geological Survey.

